SPECIAL COLLECTIONS - MEMBERS.
WALTER FRYERS 1985-1989

UNIVERSITY OF ALBERTA ARCHIVES
Accession No. 96-123.
Item No. 135
Box No. 4

Digitized by the Internet Archive
in 2013

http://archive.org/details/fryerswaltedmont00unse_3

E. R. McBurnie
528 E. 10th Street
NORTH VANCOUVER, B.C.
PH. (604) 987-3748 V7L 2E6

March 4,1989

Walt Fryers
11515 - 39 Ave.
Edmonton T6J OM5

Dear Walt:

Thank you for your letter and enclosure,"La Nina's Big Chill".

This is a very interesting piece of information, but one that I do not have the education and ability to comment on. I would need the address of the publication before considering reprinting.

Regarding your suggestion that there is a lot more room for research out there, I agree, but very few people seem interested in anything but money. Even exploiting popular fears and emotions gets no response. Anything at all that smacks of science and engineering in society moves people to turn and run like hell. They are still teaching kids in school that money is the dominent factor in our lives.

Personally, I have been asking to have someone with more ability and energy than I have to take over, but nothing has happened yet. However, I will send this article on to CHQ as usual and ask for permission to print.

Nice to hear from you, and I hope you are both hanging on to your best health. (type ribbon ran out).

Yours truly,
Ed McBurnie
Ed McBurnie

11515 39 Ave.,
Edmonton, Alta.
T6J 0M5

18 Feb 89

Editor,
Technocracy Digest,
3642 Kingsway,
Vancouver, B.C.   V5R 5M2

Dear Ed:

I think you might be interested in the enclosed article, titled: "La Nina's Big Chill Replaces El Nino", from Research News of August 16, 1988, and reprinted in "The Forecaster" of the Canadian Meteorological and Oceanographic Society to which I belong.

I question Technocracy's habit of riding trendy causes to exploit popular fears and emotions. There is a lot~~s~~ of solid science, technology and general educational material to be dealt with.

I am an enthusiastic environmentalist, but it appears to me that there is room for a lot more research in some directions before we encourage a panic reaction.

Yours truly,

Walt Fryers.

La Niña's Big Chill Replaces El Niño

The cooling of El Niño's unusually warm waters in the Pacific will alter weather and probably cool the "greenhouse," at least temporarily

If it isn't one thing with the world's weather it's another. The capacity of El Niño's warm Pacific waters to alter weather patterns—from the Indian monsoon and Winnipeg's winter cold to the temperature of the globe—has been well known for years. Now it seems that El Niño's mirror image, a pool of colder than normal water in the tropical Pacific called La Niña, has the opposite effects of El Niño. Among those effects in the coming year could be a dry winter for the southeastern United States and a reversal of the putative greenhouse warming. By this fall La Niña could also chill enough of the globe to lower its mean temperature, raising further doubts about the recently popularized notion that the greenhouse is behind the current global warming.

The present situation in the tropical Pacific is an unusual one in the recent history of El Niño. A year ago the temperature of surface waters in the central tropical Pacific was about 1.6°C above normal for that time of year, a clear sign that the exceptionally long-running El Niño that had started a year earlier was still going strong. This was the first El Niño since one of the strongest of the century struck in 1982–83. Before that there was the El Niño of 1976–77.

By December of last year El Niño's fate seemed to be sealed. Both human and computer model forecasts were calling for an end to the warm event by summer. But some of the models, and that of Tim P. Barnett of Scripps Institution of Oceanography in particular, were calling for a temperature drop to distinctly cool waters. Modest temperature anomalies persisted into March, but they were followed by a precipitous drop to 2°C below normal by June. That is about as cold as the tropical Pacific can get as strong winds draw cold water up from several hundred meters beneath the surface.

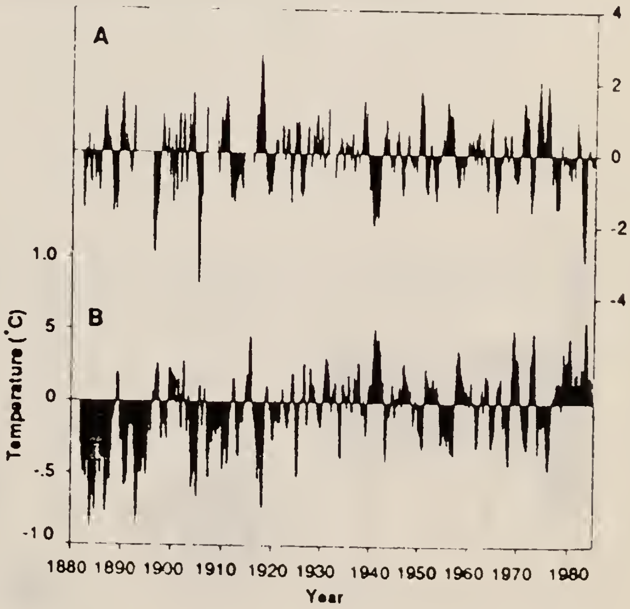
A relatively cold (24°C) equatorial Pacific has not been seen for some time. Raymond Bradley of the University of Massachusetts in Amherst, Henry Diaz of the National Oceanic and Atmospheric Administration in Boulder, and George Kiladis and John Eischeid of the University of Colorado have found that, by their definition, there were no cold events between 1975 and 1988, a unique hiatus in a record that goes back to 1881. Cold events had recurred about 4 years apart on average. Recurrence intervals were as long as 10 years.

The chilling of the tropical Pacific had always been seen as a part of the El Niño cycle, but it was a neglected phenomenon. It did not have a catchy name. It did not seem to have socially significant effects, such as the collapse of the anchovy fishery off Peru or the failure of the Indian monsoon. It seemed more difficult to define. And, unlike El Niño, it seemed to lack a practical mechanism for influencing the atmosphere outside the tropical Pacific.

In 1985 George Philander of the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, attempted to emphasize the complementary natures of the warm and cold phases of the irregular oscillation of the Pacific's water and atmosphere by naming the cold phase La Niña, or The Girl. That seemed to have more character than cold event or cold phase and to be preferred over anti–El Niño, which in Spanish would be read as anti–Christ Child.

The name La Niña has been slow to catch on, but that could change as studies point up its coequality with El Niño. By last year Chester Ropelewski of the National Meteorological Center in Camp Springs, Maryland, had already shown in a study with colleague Michael Halpert that El Niño is associated with drier than normal conditions in southeastern Africa, India, the western Pacific including Australia, and northern South America and with wetter conditions in the central Pacific and southeastern United States. They had not looked at La Niña, but Ropelewski was beginning to think that some people were making too much of La Niña and its power to change the weather. "I was doing a study to show that it wasn't that simple," says Ropelewski. "It turns out that it is."

From Ropelewski's current work on precipitation and published and ongoing work by Bradley and his colleagues on temperature and precipitation, it seems that La Niña generally has the opposite effect of El Niño in a given area. An El Niño Indian monsoon is usually drier than normal, as in 1986 and 1987, and a La Niña monsoon is wetter than normal, as is the case this year. In North America, the coming fall-winter-spring period in the southeastern United States will most likely be drier and warmer than normal, which would be no help at all for drought-stricken areas there. And, too late to help the Winter Olympics in Edmonton, this winter should be colder than nor-



A correlation *between the swings from El Niño (expressed as a negative Southern Oscillation Index or SOI in (A) to La Niña (positive SOI) and land temperatures in the tropics (B) has been found. Note the absence of La Niñas since 1975 and the corresponding abnormal warmth of the tropics, which cover almost half the globe.*

R. Bradley et al., © Nature

mal in western and south-central Canada and perhaps the U.S. northern tier states.

La Niña may affect such matters of narrow interest as the Olympics, but it also may play a role in the trendiest climate topic of the moment, detecting the global greenhouse warming. James Hansen of the Goddard Institute for Space Research touched off the biggest climatological hullabaloo since the bitter winters of the 1970s when he testified on Capitol Hill in the midst of a searing drought that the greenhouse warming is here. He said the global warming since 1965 is statistically significant, which no researcher would argue with. He said the warming is consistent with models predicting the greenhouse warming, another undisputed fact. Then he concluded that "the global warming is now sufficiently large that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect."

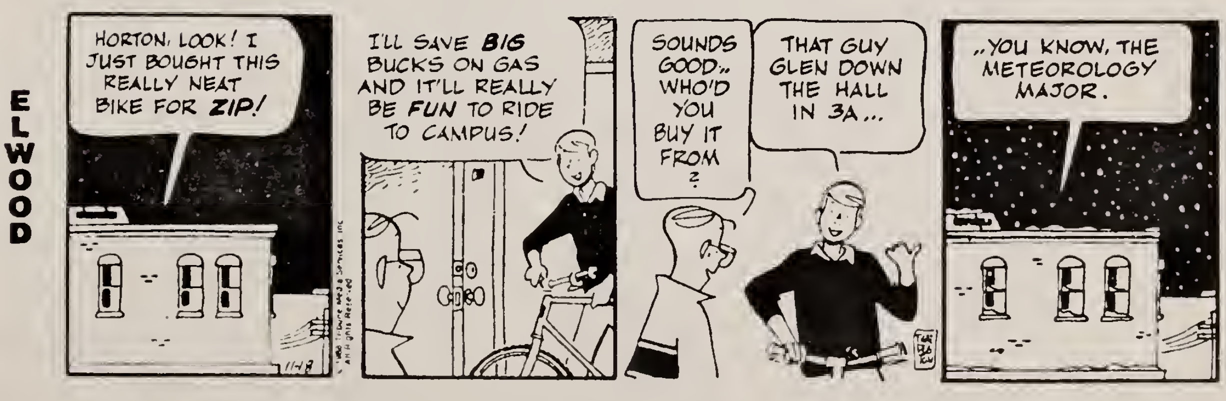
That is where most every climate researcher in the country draws the line. The size of the present warming is not a unique indicator of its cause at this point, they argue. Any number of climate-changing mechanisms could be at work, alone or in combination. Clearly, El Niño was behind the record warm years of 1987 and 1983 (*Science*, 13 May, p. 883). The first half of 1988 has been running at a record warm pace too, but then, as Kiladis notes, there is about a 6-month lag between a temperature switch in the tropical Pacific, and its effect on the global atmosphere. "It's almost certain," he says, "that in late 1988 and early 1989, the mean temperature of the tropics equatorward of a latitude of about 30° will be below normal." That area constitutes half the area of the globe. "Unless the tropics are offset by higher latitudes," says Kiladis, "the globe will be colder" this winter.

This La Niña, which is likely to continue into next spring, could at least temporarily return the globe to temperatures typical of the 1950s or even the 1920s. The last La Niña before the present one began in 1975. The last year the average global temperature was below the mean for the period 1940 to 1960 was 1976. The abrupt jump to the warmth of the 1980s came shortly thereafter. Whether La Niña's absence contributed to the global warming is unknown, but that is the sort of point that many climate researchers would like to make. It is too early, they say, to be so certain about such a poorly understood phenomenon as global climate.

■ **Richard A. Kerr**

ADDITIONAL READING

R. Bradley, H. Diaz, G. Kiladis, J. Eischeid, "ENSO signal in continental temperature and precipitation records," *Nature* 327, 497 (1987).


ELWOOD
HORTON, LOOK! I JUST BOUGHT THIS REALLY NEAT BIKE FOR ZIP!
I'LL SAVE BIG BUCKS ON GAS AND IT'LL REALLY BE FUN TO RIDE TO CAMPUS!
SOUNDS GOOD.. WHO'D YOU BUY IT FROM ?
THAT GUY GLEN DOWN THE HALL IN 3A...
..YOU KNOW, THE METEOROLOGY MAJOR.
11-8

~~Master copies~~

Copies to Ron.
John Gregory
Howard Renwick
John Teale.

Comments on a Recent General Mailing from CHQ Technocracy to Members-at-Large

I suggest that the covering letter accompanying the issue of the 1988 Membership Cards is worth a second look.

The last two paragraphs contain nothing that would reveal the intrinsic and unique nature of Technocracy's original concepts and design. As written they could be authored by any well meaning liberal, humanitarian, socialist, or even communist. It is an idealogical and populist approach on an emotional level.

And it is quite wrong, in my opinion, to say: "Technocracy is the only program on this Continent with the intent of improving the living standard and security of all citizens on this Continent." (Emphasis on 'only' is mine.) It is quite the reverse. Just about all the other programs are promising just that, at least nationally. It is a political type of statement.

It is my impression that the message conveyed in those two paragraphs is not a careless abberation, uncharacteristic of the organization in recent years. Rather it reflects an attitude of subjective reaction now assumed by spokesmen for the organization. They depend primarily on such devices as fear mongering, down crying, negativism of every kind, coupled with exhorting the faithful and belaboring the public-at-large with glittering generalities, and unsupported rhetoric, endlessly repeated. Where is the scientific substance that gave birth to this body of thought - Technocracy. Is there no one of technical competence? No, there is not!

Walt Fryers. 1/2/88

CHQ Technocracy Inc.
POB 238
Savannah OH 44874

To: Members-at-Large

Subject: Membership Card for 1988

1. Enclosed is your Membership Card showing your dues paid thru December 31, 1988, as an MAL of Technocracy Inc.

2. Here are some of the ways an MAL can promote the objectives of the Organization:

   a. Wear a monad pin or button at all times.
   b. Turn your car into a symbol for Technocracy by applying the 6½" by 11½" magnetic signs to the doors. These signs are available from CHQ for $4.00 each (U.S.funds.)
   c. Keep your subscription to Technocracy Field Magazines up-to-date. $10.00 annually brings both quarterlies, The Northwest Technocrat and Technocracy Digest.
   d. Technocracy-Technological Social Design is a dynamic reference book for study. It costs $2.00 (U.S.funds) from CHQ or The Northwest Technocrat.
   e. Ask your local librarian to accept a gift subscription and a TTSD, and make them available to his or her readers.
   f. Distribute Technocracy literature, both free Briefs and Pamphlets for sale. (A list of items available from CHQ is enclosed.)
   g. Write letters to editors of newspapers and other periodicals. Send copies of such letters to CHQ.
   h. Organize study groups.
   i. Financial contributions to the Organization also help.

3. The American heritage certainly justifies any American demanding a far higher standard of living than that of the present average. If you demand it for yourself alone (or for your minority group), you will gain nothing but the well deserved contempt of others. If you demand it for all Americans, and only incidentally include yourself, you are above all distrust and indignation. You would not escape ridicule, however, for there will be the simple-minded and reactionaries who always oppose any idea of progress or advancement as a matter of policy. Ridicule coming from these sources will only add to the prestige of your program. You will gain support from people in all walks of life, in all geographical localities on the Continent, and in all social strata.

4. Technocracy is the only program on this Continent with the intent of improving the living standard and security of all citizens on this Continent. Technocracy offers you the only pathway out of the woods of the Price System.

CHQ
Technocracy Inc.

11515 39 Ave.,
Edmonton, Alta.
T6J 0M5

22 Feb 88

Greetings John:

I received your note of 22 Jan 88 along with the enclosed reprint titled "The nuclear Reactor accident at Chernobyl, USSR" by Bernard L. Cohen, as published in the American Journal of Physics in December 1987. You asked for my comments. Yes, I agree with the article: the threat of Chernobyl has been vastly overrated in the media !

I found the article, on reading and re-reading it, to be very interesting and authoritative, if a bit technical. Co-incidentally I had very recently read another article at our local Public Library Branch on nuclear energy that seemed relevant so I tried to look it up. I was unable to find it again, but the gist was to the effect that the American style of mega plants would be no more, having been 'killed' by distorted media attention which led to excessive emphasis on irrational safety measures of great cost, making them uneconomic. He offered the possibility of smaller but totally safe nuclear plants at reasonable cost. He did not specify exactly what the design of such plants would be. He was an engineer at MIT, I believe.

In my search at the library I came across a book which I can highly recommend which deals with this subject exhaustively, but is very readable for the most part. It is by the same author as the article you sent me: Bernard L. Cohen. His book is titled: "Before it is Too Late", with a follow-up lead: "A Scientist's Case FOR Nuclear Energy". This should be in every Technocracy library and read by every Technocracy writer and speaker. It is not only a good treatise on the subject, it is also a good example of how science can deal with a controversial subject. And it is an indictment of the price system press, politics, economics, etc., indirectly. In our eyes it may even be a challenge to the democratic adversarial method of dealing with vital issues, such as the generation of energy.

I've selected a couple of quotes to include here. From page 70: "How did this gross public misunderstanding come about? The public gets its information from the media, so the media must be responsible. But why have the media given such a distorted view? .... For the first time in ~~history~~ the history of our civilization, a n industry has exerted an intense effort to determine its environmental effects in advance. Thousands of man-years of effort have been expended in dreaming up all the things that could go wrong in nuclear plants and in estimating the possible consequences. With all of this effort, some very damaging scenarios can be developed, although they have very small probabilities." Add to this the fact that radio-activity is susceptible to very accurate and quantitative measurement even in the most minute quantities, and that it has entered the public domain in so many ways (medicine, etc.) relatively recently.

Chapter 9 is "The Solar Dream". (This is a good analysis of solar vs. nuclear energy.) He concludes: "The problem is that our case is based on science, while the antinuclear case is based on political philosophy. When a nation whose welfare is highly dependent on technology makes vital technological decisions on the basis of political philosophy rather than on the basis of science, it is in mortal danger." He supports this statment very well.

Today's issue of the Edmonton Journal provides an example of media distortion of the nuclear question. The article had a banner headline across the whole width of the front page: "Chernobyl hastened 42,000 deaths - U.S. study". The write-up took up about one-quarter of the front page. It appears to be the work of a statistician, mostly. One Dr. Jay Gould. He is apparently neither a medical doctor nor a physical scientist. But he presents his findings as a correlation between the Chernobyl accident and a consequent four month increase in death rates in some parts of the U.S. Had he consulted with medical and physical scientists such as Bernard L. Cohen he would not have jumped to such ridiculous conclusions as the article presents. It is a fear-mongering article, using terms such as 'most disturbing single statistic, the one that is really scary'; 'chilling stories'; 'terrible rumors';'incredible jumps in mortality'. The writer - one Robin Ludlow - got a lot of lines on page one, but must share the credit or blame for this garbage with the Journal Editor who let him get away with it. I'll leave it to someone else to debunk this article in detail. The article you sent me provides a lot of information that puts the lie to Gould's thesis. For instance, on page 1081, we read that radioactive Iodine has an 8-day half-life, decaying rapidly into Xenon (a noble gas of negligible health effect) and then into Cesium 'that does harm by depositing on the ground where its gamma radiation continues to expose those nearby for many years. It can also be picked up by plant roots and there y get into food which leads to exposure from within the body. In either case, it can cause several types of cancer or leukemia.' These radioactive elements can be readily detected. Measurements of total radioactivity a round Chernobyl gives estimates of an average dose of only 12 rem total within 30 km. of the site. The resulting increase in cancer deaths over the number normally expected will be so few as to be undetectible epidemiologically. Beyond 30 km the effects are even less.

---

23 Feb 88

The Journal article includes the hysterical suggestion that the Chernobyl accident aggravated death rates from various diseases such as AIDS. Cohen's book, on page 30, states: "I am often asked whether there aren't other than cancer and genetic defects induced. Careful studies among the survivors of the atomic bomb attacks on Japan where 24,000 people were exposed to an average of 130,000 mrem each, revealed no such evidence. Moreover, our understanding of how various diseases develop leads us not to expect other diseases from low-level radiation." I'll go with Cohen on this question. (The term 'mrem' is for millirem, a measure of radioactivity - very small). Ludlow, in the Journal article, uses some work by Dr. Abram Petkau, out of context, to support his ideas. I am pleased to say that the Edmonton Journal has, this morning, printed a contradiction of the Ludlow article, again on the front page, and same position. I'm enclosing copies of both articles. They constitute a good example of why the public is so confused about nuclear energy.

I am also enclosing copies of CHQ's covering letter for renewed memberships of MALs, and my comments on it. I do feel that Technocracy Inc. has lost its credibility and its appeal especially to people of technical and scientific sophistication, and indeed, to the public at large. The redirection and restructuring that would be required to give it new life will take a long time, and there is no sign of it yet. In general it sounds more like a political opposition party, constantly nagging away at the status quo. How tiresome. And how futile. Where is the scientific thrust that xxxxxx focussed on the unidirectional and irreversible progression of science and technology that gave rise to the concepts of Scott's Technocracy in the first place? I suppose we must wait for a super-crisis to give rise to new leadership within and without the organization.

I'll end my dissertation now, and hope you feel I have responded to your note and question adequately. My wife Edith has suffered a relapse to her MS handicap and needs my support more than ever.

Your Technocracy associate, Walt Fryers.

P.S. I dont think it is too late for nuclear power (energy) in the United States. Even if the U S. continues in its paralysis on this technology, other nations will take up the challenge and lead the way, until the U.S. recovers its objectivity. I suspect that part of the 'turn-off' on nuclear energy was the simple fact that it was not really needed and that an uneconomic surplus loomed ahead.

Scientists doubt Chernobyl link to deaths

By DON THOMAS
and DAVID HOLEHOUSE
Journal Staff Writers

Federal government scientists are skeptical about a U.S. study that links a jump in death rates with fallout from the Chernobyl nuclear reactor explosion.

And a University of Alberta radiation specialist says he doesn't think Albertans should panic over the study.

"You are really stretching the limits of explanation to say that these deaths are related to Chernobyl," said radiation protection officer Carl Schumaker of the U of A. "People in the know would really question that kind of cause-and-effect relationship."

He was commenting on a study published in The Medical Post suggesting U.S. death rates involving AIDS, pneumonia, infectious disease and infant mortality shot up in the four months after the Chernobyl explosion.

Schumaker said he knew of no similar studies in Canada.

"There was relatively little radioactivity deposited in North America," he said. "Most people would agree it wasn't an amount to contribute to any health concern."

Chernobyl radiation was not picked up in Edmonton in significant quantities, he said.

Statistics Canada figures show Canadian deaths in the four months after Chernobyl dropped slightly from the average for 1983-85.

In Alberta, there were 218 or 0.85 per cent more deaths in the four months compared with the same period in 1985.

Health officials say such changes are statistically meaningless.

The Post report said as many as 42,000 deaths in the United States may have been hastened by the effects of fallout from the April 26, 1986 explosion. Death rates rose by more than five per cent above average in some areas, it said.

The study, which also says Canadian lives might have been affected, was published by Jay Gould of the Institute for Policy Studies in Washington, D.C., and Dr. Ernest Sternglass of the University of Pittsburgh.

Dorothy Meyerhof, radiation hazards chief for the federal Health Department, said: "I don't think the results are credible. They're contrary to everything that is so far known about the effects of radioactivity."

Increased deaths due to AIDS, pneumonia and infectious diseases have not been scientifically linked to radiation exposure, she said.

Radiation levels in Canada after Chernobyl were up less than one per cent, which is within the normal range due to sunspot activity and other causes, she said.

"When people are exposed to radiation at much higher levels than those . . . the health effects don't show up for several years."

The Medical Post report is popular press "gee whiz stuff" that wasn't checked out by the scientific community and doesn't show how the authors made their conclusions, she said.

In Ottawa, Health Minister Jake Epp said his officials are reviewing health statistics after the report, but a department official said there are no plans for a similar Canadian study.

The U.S. report said work by Dr. Abram Petkau of the Whiteshell Nuclear Physics Lab in Pinawa, Man., indicates that chronic exposure to radiation can weaken the body's immunity to disease.

Petkau's research indicated that long-term exposure to low-level radiation may be more damaging to red blood cells than brief exposures to high doses.

But Petkau said he can't see what relationship that has to "the kind of things in the report."

"Our data certainly does not prove that kind of cause-and-effect relationship."

Petkau said he'd be "very surprised that they have the right explanation."

0 558295 22
Published daily
by the
proprietor,
Southam Inc.,
at The Journal
Building,
Edmonton, Alta.
T5J 2S6.
Second class
mail registration
number 0566.

EDMTN JOURNAL. 23 FEB 88.

Chernobyl hastened 42,000 deaths—U.S. study

By ROBIN LUDLOW
Southam News

OTTAWA — The stunning results of a U.S. study suggest the Chernobyl nuclear disaster probably hastened the deaths of as many as 42,000 Americans.

Canadian lives may have been affected as well, the study says.

Analysis of U.S. death rates for the four months following the April 26, 1986, reactor explosion in the Soviet Union show:

- Death rates increasing by more than five per cent above average in some areas, and directly related to areas with the highest radioactivity in rain and milk.
- A 60-per-cent increase in the number of AIDS-related deaths.
- A 22.5-per-cent increase in deaths from infectious diseases.
- An 18-per-cent increase in pneumonia deaths.
- A 14-per-cent increase in infant mortality rates coupled with a record low in live births.
- An overall increase of 1.4 per cent more than the average deaths for the same period in the previous 80 years. Statistically, there is a one in 10 million chance of this occurring by chance.

The figures appeared for the first time in Canada in the current issue of The Medical Post.

Most of the deaths, about 30,000, were people over age 65 but after excluding deaths by accident, violence, suicide and drug abuse, there was also a five-per-cent increase in deaths in the 25-34 age group.

"This is the most disturbing single statistic, the one that is really scary," the publication quotes Dr. Jay Gould, chief of the research group, as saying.

Gould, an expert in computer analysis of medical data, is a fellow of the Institute for Policy Studies in Washington, D.C.

The study group checked U.S. death figures, which became available late last year, because of "chilling stories" about radiation effects in Europe.

"We heard terrible rumors about the decline in live births in Poland," Gould said.

After analysing U.S. patterns, the researchers found that 692,000 Americans died in the four months after Chernobyl. Normally 650,000, at the most 660,000 deaths, would be expected.

The jump of 32,000 to 42,000 deaths was mostly among people who were already ill or who had weakened immune systems that were further damaged by low levels of radioactive fallout.

"That radiation accelerated the process," Gould said.

He said the Chernobyl explosion released in a matter of days as much radiation as in all the years of atmospheric bomb testing.

Gould said that during the four months of fallout, "We had a series of statistically incredible jumps in mortality."

The study also found a huge decline in live births which matched the levels of radioactive iodine measured in the rain and milk of each American state.

Death rates in states with low summer rainfall were normal.

States reporting the highest rainfall, such as Oregon and California, also had the highest iodine levels and the highest death rate increases.

The Pacific Northwest was the most affected region with a 5.6-per-cent summer mortality increase. It also had the heaviest rainfall and the highest levels of radioactive iodine in rain and milk.

Gould said British Columbia was probably similarly affected because it borders the area with the highest U.S. levels.

Canadian Health Protection Branch officials reached at home on the weekend were unaware of the report but planned to investigate today.

Dr. Abram Petkau, manager of medical biophysics at the Whiteshell Nuclear Physics lab at Pinawa, Man., has been working on a theory of damage from low-level radiation for the past 16 years.

He has shown that low levels applied over a long time more effectively break down blood cell membranes than high levels for a short period.

The immune system depends on blood cells and if they are damaged, the immune system is weakened, increasing susceptibility to illness — the same process that occurs with AIDS.

"It's like a slow burn," Petkau says. "All the radiation effect does is strike the match."

0 558295 22

Published daily by the proprietor, Southam Inc., at The Journal Building., Edmonton, Alta., T5J 2S6. Second class mail registration number 0566.

EDM

TN JOURNAL 22 FEB 88.

John A. Taube
(415) 334-3733
55 CHUMASERO DRIVE #7
SAN FRANCISCO, CA 941

January 22, 1987

Hi, Walt:

I alway appreciate any comment you have on what I send you.

I would especially like to get your comments on the enclosed as it is a bit to complicated for me.

J.

The nuclear reactor accident at Chernobyl, USSR

Bernard L. Cohen
University of Pittsburgh, Pittsburgh, Pennsylvania 15260

(Received 4 December 1986; accepted for publication 14 March 1987)

The sequence of events and the consequences of the nuclear reactor accident at Chernobyl, USSR in April 1986 are reviewed. The background material in nuclear reactor and nuclear explosion physics required for understanding these events is extensively explained, and the differences between U.S. and Chernobyl-type reactors are pointed out.

I. INTRODUCTION

An explanation of the accident at the nuclear power plant at Chernobyl, USSR, in April 1986, requires an understanding of many concepts of reactor physics and nuclear weapons technology that are not ordinarily taught in physics courses. A discussion of that accident therefore offers a unique opportunity to teach those concepts in an interesting context. This article presents such a discussion.

II. THERMAL VERSUS FAST REACTORS

The basis for nuclear reactors is a *self-sustaining chain reaction* in which the neutrons that induce nuclear reactions are produced in those reactions. The quantity of interest here is η, defined as

$$\eta = \frac{\text{neutrons produced in a reaction}}{\text{neutrons consumed in a reaction}}.$$

Since these reactions are the only source of neutrons, the requirement for the process to be self-sustaining is that the average value of η, $\bar{\eta}$, be

$$\bar{\eta} \geqslant 1.0. \tag{1}$$

When a neutron strikes a ^{235}U nucleus (hereafter U-235), it usually induces a fission reaction in which up to six neutrons are emitted; as an average, η(U-235) = 2.0. When a neutron strikes a ^{238}U nucleus (hereafter U-238), the reaction is nearly always (n,γ) in which no neutron is emitted; thus η(U-238) = 0. The condition (1) for a chain reaction, $\bar{\eta} \geqslant 1.0$ therefore requires that at least half of all neutrons react with U-235.

Neutrons produced in fission reactions emerge at an average of 1 MeV. Neutrons of this energy are called "fast." Cross sections for fast neutrons are roughly equal to πR^2 where R is the nuclear radius which varies very slowly with nuclear mass. Thus the fast neutron cross sections for U-235 and U-238 are about equal, and to have as many neutrons interacting with U-235 as with U-238, the condition for a chain reaction, there must be at least as much U-235 as U-238 in the fuel.

Since natural uranium contains 99.3% U-238 and only 0.7% U-235, it would seem not to be a suitable fuel for such a chain reaction. However, there is a trick available to solve this problem. For neutrons of thermal energy (i.e., the energy of the molecules in the surrounding material, 0.025 eV at 300 K), the cross sections are σ(U-235) = 590 b (1 b = 10^{-24} cm^2), σ(U-238) = 2.7 b. (There are good nuclear physics reasons for this large difference.) Thus for thermal energy neutrons, the ratio of those interacting with U-235/U-238 is $(0.7\times590)/(99.3\times2.7) = 1.5$, the fraction interacting with U-235 = $1.5/(1.5+1.0) = 0.60$, and $\bar{\eta} = (0.60\times2.0) = 1.20$. This satisfies Eq. (1) if all neutrons interact with uranium, and there can even be a chain reaction if $0.20/1.20 \approx 17\%$ of the neutrons interact with other materials (for which $\eta = 0$) or escape out the sides.

The trick then is to reduce the energies of the neutrons from ~1 MeV to 0.025 eV, a factor of nearly 10^8, before they interact. This is done by adding a "moderator," a material with whose nuclei neutrons can have scattering collisions without being captured. In an elastic collision, a struck nucleus of mass A (in atomic mass units) recoils with an average of $1/(A+1)$ times the energy of the incident neutron, and the neutron energy is reduced by this amount. Clearly, an efficient moderator must have a low A-value. The other requirement for a moderator is that it has a very small cross section, σ_c, for capturing neutrons [ordinarily in (n,γ) reactions]. From the first requirement, ^{1}H (ordinary hydrogen, H) is optimal, but it has an uncomfortably large σ_c. The next lightest nucleus is ^{2}H (deuterium, D), and it has a very small σ_c. Another possibility is ^{12}C (ordinary carbon, C) which has an uncomfortably large A value, but a very small σ_c.

Gases are not suitable as they do not have enough atoms per unit volume, but oxygen also has a very small σ_c that allows hydrogen to be used in the form of water. The three candidates for moderators are therefore H_2O (light water), D_2O (heavy water), and C (graphite). In 1941 the question was whether these moderators could be used with natural uranium to produce a self-sustaining chain reaction.

With heavy water it is very easy, but production of D_2O requires separation of hydrogen isotopes. During World War II, Germany was using this approach, setting up a large hydrogen isotope separation plant in Norway, where the large amount of electric power required was readily available. However, the British destroyed the plant in a spectacular Commando raid that was later vividly portrayed in a feature movie. That was the end of the German nuclear weapons program. Canadian nuclear power reactors now use natural uranium with heavy water as a moderator.

With graphite as a moderator it is possible to obtain a self-sustaining chain reaction with natural uranium fuel if the graphite is extremely pure. Even tiny amounts of impurity materials with average σ_c capture enough neutrons to make $\bar{\eta} < 1.0$ and stop the process. Graphite of sufficient purity first became available early in World War II and this allowed Fermi and his group at University of Chicago to achieve the first nuclear chain reaction in 1942. All of the reactors built during World War II used natural uranium moderated by graphite.

Ordinary water, H_2O, it turns out, cannot be used in conjunction with natural uranium to obtain a self-sustain-

© 1987 American Association of Physics Teachers

ing chain reaction; the hydrogen absorbs too many neutrons. Actually, this is fortunate, for otherwise it would be very easy to build nuclear reactors and Hitler would have had nuclear weapons during World War II. In order to make a reactor with H_2O moderator, the uranium must be enriched to at least 2.5% U-235. Commercial nuclear power plants in the United States use this technology, called light water reactors (LWR), with about 3% enrichment. But for enrichments less than 2.5%, H_2O is a "poison"; that is, its principal effect is to *absorb* neutrons, making it *more* difficult to achieve a self-sustaining chain reaction.

III. COMPARISON BETWEEN U.S. LWRS AND CHERNOBYL

In American LWRs, water is the moderator and is therefore vital to the continuation of the chain reaction and its energy release. If the water should somehow be lost [a loss of coolant accident (LOCA)] the chain reaction instantly stops. If for any reason the temperature rises, water becomes less dense or boils, which reduces the amount of moderator, which slows down the chain reaction, which reduces the energy output, which lowers the temperature. Thus, a LWR is *stable* against a temperature increase—an increase in temperature causes the temperature to decrease. A very graphic example of this stability is research reactors used to produce millisecond pulses of neutrons. A control rod is literally shot out with compressed air, making the reactor supercritical and hence producing a very high neutron flux, but within a few milliseconds, this raises the temperature to the point where the chain reaction is shut down, stopping the neutron production.

With all this stability, one might ask how there can be accidents like Three Mile Island in U.S. reactors. That accident was *not* due to a runaway chain reaction. In fact, the chain reaction was shut down within seconds of the first failure. The problem there, and in essentially all anticipated accidents in LWRs, is that heat continues to be produced by residual radioactivity, at a rate of a few percent of the power generated by the chain reaction. In the absence of cooling, this heat is sufficient to melt the reactor core, but that process takes much more time and in general does not involve violent explosions.

The Chernobyl-type reactor is moderated by graphite, but in order to produce the steam needed for electricity generation, the uranium fuel is surrounded by flowing water being boiled into steam. The presence of this water requires that the uranium be enriched to 2.0% U-235, but at this low enrichment, water still acts as a poison, tending to slow down the chain reaction. That means that if the water is somehow lost, the chain reaction accelerates, a potentially dangerous situation. If for some reason the temperature rises, there is more boiling and therefore less water, which means less poison, which accelerates the chain reaction, which produces more energy, which causes further increase in temperature. In a word, the reactor is *un*stable against temperature increase.

Why would anyone build a reactor that is unstable against temperature increase, and tends to "run away" if the water is lost? The Soviet designers reasoned that these problems could be easily taken care of by active systems to insert control rods. The U.S. design policy is not to depend on active systems for safety since active systems can fail; it is much better to depend on the laws of physics, which cannot fail. The Soviets do not accept that policy, but much more important, Chernobyl-type reactors are designed to produce bomb grade plutonium (Pu) while they generate electricity. In order to understand how this affects the reactor design, it is necessary to understand the basics of nuclear bombs.

IV. NUCLEAR BOMBS

The requirement for explosive power is *not* that large amounts of energy be liberated—burning a pound of coal liberates far more energy than burning a pound of TNT. The requirement is, rather, that the energy be released within a very short time. This would be necessary in any case with a nuclear bomb because a "critical size" must be maintained if the chain reaction is to continue. That means that as the system is blown apart, energy generation ceases after the fragments seperate by a few centimeters. Rifle bullet velocities range up to 3000 ft/s, so perhaps bomb fragments fly apart at 10 000 ft/s $= 3 \times 10^5$ cm/s. That means that energy release ceases after about 10 μs.

In the thermal reactors we have been describing things happen much more slowly. The velocity of a thermal neutron is about 2×10^5 cm/s, and it must travel a path length of perhaps 20 cm to diffuse back into the fuel where it can induce a fission reaction, requiring a time of $(20/2 \times 10^5 =)10^{-4}$ s or 100 μs. This (plus the $\sim 10^{-5}$ s required for a neutron to be thermalized) is the time for a "generation" of neutrons in a thermal reactor, i.e., the time from when a neutron is "born" in a fission reaction until it induces a fission reaction to produce the next generation of neutrons. It is analogous to the 30-year generation for people, except that in the latter case the parents do not die as their offspring are produced as in the case of neutrons. Clearly the 100-μs generation time for a thermal reactor is not consistent with the 10 μs available for energy release in a nuclear bomb.

A nuclear bomb must therefore be a "fast" reactor, in which the neutrons are not slowed down. A neutron emerges from a fission reaction with a speed of about 10^9 cm/s. The cross section for it to interact $(\sim \pi R^2)$ is about 2×10^{-24} cm^2 in uranium, which contains

$$\frac{6 \times 10^{23}\text{atoms/mol}}{235 \text{ g/mol}} \times 15 \frac{\text{g}}{\text{cm}^3}(\text{density})$$
$$= 4 \times 10^{22} \text{ atoms/cm}^3.$$

The average distance a neutron travels before interacting is then $(2 \times 10^{-24} \text{ cm}^2/\text{atom} \times 4 \times 10^{22} \text{ atoms/cm}^3)^{-1} \cong 10$ cm, which takes a time $(10 \text{ cm}/10^{9} \text{ cm/s} =)10^{-8}$ s, or 10^{-2} μs. This is the generation time for fast neutrons.

Since a fast neutron has the same cross section for striking U-238 and U-235, our requirement that at least half of the neutrons strike U-235 means that the uranium must be enriched to at least 50% in U-235. That might make the reactor just barely critical, but in a bomb it must be supercritical. U. S. bombs use an enrichment of over 90%, which means that 90% of the neutrons hit U-235 nuclei for which $\eta = 2.0$, giving an average $\bar{\eta} = 1.8$. Considering the fact that some neutrons escape out the sides, perhaps the true value of $\bar{\eta}$ in a bomb is 1.5. That means that in each generation, the number of neutrons is increased by a factor of 1.5.

Next we estimate the number of generations required to release the required energy. From energy equivalences, each pound of material undergoing fission releases as much energy as 9000 metric tons (9 kT) of exploding TNT. A 1-megaton (1000 kT) bomb therefore requires the fission of about 100 lb of U-235, or about 10^{26} atoms. If X is the number of generations of neutrons required,

$$(1.5)^X \cong 10^{26},$$

which may be solved to give $X = 150$ generations. With a 10^{-2}-μs generation time, this process requires $(150 \times 10^{-2} =)1.5\ \mu$s, well within the 10-$\mu$s time available before the material is blown apart.

A material in which about 90% of the nuclei are fissile is, therefore, a suitable fuel for a nuclear bomb. One example is highly enriched uranium. An alternative that has certain advantages (e.g., a larger value of η) is plutonium-239 (Pu-239).

V. PRODUCTION OF PLUTONIUM

Plutonium does not occur in nature, but it can be produced by neutron capture on U-238 to yield U-239, which then undergoes two relatively rapid beta decays to become Pu-239. Plutonium is thus produced simply by putting U-238 into a nuclear reactor. But there is a great deal of U-238 in essentially all reactors; e.g., the fuel in American LWRs is 3% U-235 and 97% U-238, and consequently, a great deal of Pu-239 is produced. This is what allows the fuel to remain in the reactor for a year or more; as the U-235 burns out, it is replaced as a fuel by the newly produced Pu-239, to the point where two-thirds of the energy release is from fission of Pu-239.

If the goal is to produce Pu-239 as a bomb material, the uranium is removed from the reactor, dissolved, and chemically processed to seperate out the plutonium.

For a reactor generating a given amount of energy, the quantity of plutonium produced is proportional to the ratio of U-238/U-235, or inversely proportional to the uranium enrichment. Since a reactor moderated by H_2O requires a relatively high enrichment, it is not suitable for this purpose. Plutonium production reactors are therefore moderated by graphite (at Hanford, WA) or by heavy water (at Savannah River Plant, SC). That is why the Chernobyl-type reactor is graphite moderated.

The plutonium fuel produced for a bomb is essentially pure plutonium, but it is not pure fissile material, because there will be some plutonium-240 (Pu-240). Once a Pu-239 atom is formed, it may be struck by a neutron that results usually in fission but sometimes in an (n,γ) reaction to produce Pu-240.

The fact that Pu-240 is not fissile is not the only difficulty with this situation. Much more important is the fact that Pu-240 has a relatively high probability for radioactive decay by spontaneous fission, and fission is accompanied by emission of neutrons. In short, Pu-240 spontaneously emits neutrons. This introduces the possibility that these neutrons may cause the bomb to "fizzle."

To understand this, consider the assembly of a bomb. Initially, it must, of course, be subcritical, but to produce the rapidly escalating chain reaction, it must be highly supercritical. To go from subcritical to highly supercritical requires moving material at least something like 2 cm. This motion probably cannot be more than five times faster than a rifle bullet, or 5×10^5 cm/s. The time required for this motion is thus about $(2/5 \times 10^5 =)\ 4 \times 10^{-6}$ s, or 4 μs. If a neutron appears on the scene within this 4 μs, the chain reaction starts too soon, this generates powerful forces tending to blow the material apart and therefore preventing complete assembly, and the bomb therefore does not develop nearly its full energy release. This is called a "fizzle."

What is the probability for a neutron from spontaneous fission to appear during the assembly process? Initially, the quantity of Pu-239 in a reactor builds up linearly with time; since the *rate* of production of Pu-240 is proportional to the amount of Pu-239 and therefore increases linearly with time, the *quantity* of Pu-240 builds up quadratically with time. Thus the ratio Pu-240/Pu-239 increases linearly with time, and hence depends on how long the uranium was left in the reactor. It turns out[1] that if it was left in the reactor 30 days, the Pu-240 in a bomb produces an average of one neutron every 15 μs, whereas if it is left in the reactor 3 years as in an American LWR, a neutron can be expected every 0.5 μs. In the latter case, there will probably be several neutrons within the 4 μs required for assembly of the bomb, and a fizzle is all but certain. This highlights the problem terrorists would have in making a bomb from plutonium derived from LWR fuel. To avoid a fizzle, it is important that the uranium be left in the reactor for as short a time as possible, normally about 30 days.

In an American LWR, changing fuel requires a shutdown of at least 30 days. It is therefore clearly impractical to change the fuel every 30 days. This introduces another important constraint into the design of the Chernobyl-type reactor—fuel changing must be done without shutting down the reactor. This requires a great deal of working space above the reactor, which makes it impossible to enclose the system in a *containment* structure of the type used in the American LWRs.

American containments are constructed of 3-ft-thick very heavily reinforced concrete, lined with steel plate. They are designed to protect the reactor from external threats such as anything a tornado can hurl at it (e.g., a car, a tree, or a house), nearly all airplanes flying into it, any amount of explosive placed against it, etc. But in an accident situation, it is designed to *contain* any released radioactive material inside. For example, all studies of the Three Mile Island accident conclude that even if that accident had resulted in a complete meltdown, there still would have been no harm to the public because essentially all of the radioactivity would have been held inside. The Chernobyl-type reactors are without that protection. Even after the accident the Soviet scientists are still convinced that it would not be possible to add such a containment.

VI. SUMMARY OF DIFFERENCES—CHERNOBYL VERSUS AMERICAN LWRS

A LWR consists simply of 3% enriched uranium fuel in a single, powerfully built (typically 8-in.-thick steel) reactor vessel. Water flows through and serves as the moderator. It is heated by the chain reaction, and thereby acts as the heat transfer agent. In one type LWR, the "boiling water reactor," it is heated enough to be converted into high-pressure steam which is then used to drive the turbogenerator. In the other type LWR, the "pressurized water reactor," it remains as a very hot liquid which is then used to generate the required steam. If the water should be lost in an LWR, the chain reaction is automatically shut down because of lack of a moderator. LWRs are stable against a temperature change. Some of the fuel is changed every year or two, which makes it unsuitable for production of bomb grade plutonium. LWRs are protected by a full containment.

In the Chernobyl-type reactor, the moderator is 1500 tons of graphite penetrated by 1700 thin-wall tubes that contain the fuel. Water pumped through these tubes is boiled to produce the steam to drive the turbogenerator. Loss of water would cause a rapid *escalation* in the chain reaction, and the system is *un*stable against temperature changes. The fuel can be changed continuously without shutting down the reactor, making it useful for production of bomb grade plutonium. There is essentially no containment over the top part of the reactor where the fuel change is carried out (there is a cover plate designed to withstand the rupture of only one of the 1700 tubes).

One other detail about the Chernobyl reactor is relevant to the accident. The steam produced in the tubes is collected in steam separators where the water droplets contained in it are separated out by bubbling through water. All water entering the reactor passes through the steam separators first.

VII. THE EXPERIMENT[2]

With this extensive background, we are now prepared to discuss the events leading to the accident at Chernobyl. It resulted from an experiment to develop use of the stored kinetic energy in the turbogenerators ($\frac{1}{2}I\omega^2$) to operate water pumps in the event of failure of off-site electric power following an accident that shuts down the reactor. With no electric power available, the pumps would not be able to maintain cooling, and large scale melting would result. Utilizing the stored kinetic energy in the turbogenerators would be useful during the approximately 3 min required to start up diesel generators to provide emergency power. The particular problem addressed in this experiment was testing a method for maintaining the voltage as the turbogenerator slows down.

This was strictly an electrical engineering experiment, with no nuclear problems being studied. It was directed by an electrical engineer, and the reactor was run by regular operators, with no nuclear experts on hand.

The straightforward procedure would be to divert the steam away from the turbogenerator (to the condenser) leaving the turbine without a driving force, and to shut down the reactor because removal of the sink for its energy generation can cause problems in reactor operation. In fact, as is the case in all reactors, the Chernobyl-type reactor has an automatic system for shutting down the reactor if the load is lost, but that system was disabled for the experiment because they decided not to shut down the reactor. The reason for this decision is the *xenon problem*, which we now discuss.

VIII. THE XENON PROBLEM

One of the pieces into which the uranium nucleus sometimes splits in the fission reaction is ^{135}I, which undergoes further decay as

$$^{135}\mathrm{I} \xrightarrow[\beta-6.7\,\mathrm{h}]{} {}^{135}\mathrm{Xe} \xrightarrow[\beta-9.2\,\mathrm{h}]{} {}^{135}\mathrm{Cs}.$$

It so happens that ^{135}Xe has a very large cross section for capturing a neutron in an (n,γ) reaction, 2.6×10^6 b. This is 10^{10} times larger than some of the cross sections discussed above, a remarkable difference with a good nuclear physics explanation. Because of its very large cross section, ^{135}Xe is a *poison*, reducing the chain reaction rate.

When a reactor is operating, the amount of ^{135}Xe is determined by an equilibrium between its formation by decay of ^{135}I produced in fission reactions, and its destruction by neutron capture reactions. Due to its huge cross section for capturing neutrons, a ^{135}Xe nucleus rarely lasts long enough to decay into ^{135}Cs. However, when a reactor is shut down, this neutron capture stops, and the amount of ^{135}Xe increases as ^{135}I continues to decay into it. It reaches a peak after about 10 h, and then decreases as the supply of ^{135}I has been reduced by decay (removing the source) and the ^{135}Xe decays into ^{135}Cs. Thus when a reactor is shut down, the increase in ^{135}Xe poison makes it difficult if not impossible to restart the reactor for many hours. For analogous reasons, it is difficult to control a reactor after a sharp reduction in power. This is especially true for a reactor that is unstable against temperature fluctuations.

The plan for the experiment was to repeat it if necessary without delay. It was therefore decided not to shut down the reactor in the process. This added the problems associated with loss of load to the other problems faced by the reactor operators.

IX. THE EXPERIMENT (CONTINUED)

The experiment was ready to begin at 1 p.m. on 25 April, but a need for the reactor power output unexpectedly developed and the experiment had to be delayed until 11 p.m. At that time, the reactor power was reduced to achieve the power level desired for the experiment, 700–1000 MW (thermal), but it was reduced too rapidly and the resulting buildup of ^{135}Xe caused the power to decrease far below the desired level, to as low as 30 MW. This required withdrawal of control rods, and for the next 2 h the operators struggled to stabilize the power at an acceptable level. The highest power level they could achieve steadily was about 200 MW. About 1 a.m. (26 April), it was decided to go ahead with the experiment at that level.

In accordance with the original plan for the experiment, at 1:05 a.m. additional water cooling pumps were turned on—these were the ones to be powered by the stored mechanical energy in the turbogenerator during the test. No one seemed to pay attention to the fact that at the lower power level—200 MW vs 700–1000 MW—this was an excessive water supply for the reactor, forbidden by the rules, because it could lead to prompt criticality which will be explained below.

It was then noticed that the water level in the steam separators was too low. This required an increase in water flow to the steam separators, which automatically increased the water flow through the reactor, but with some time delay. This operation was carried out at 1:19 a.m.

Since water is a poison, increasing the water flow to the reactor requires further withdrawal of control rods. The automatic control rods came all the way out of the reactor, but that was still not enough. The operators had to withdraw manual control rods. As a result, a situation developed where a loss of water would make the reactor "prompt critical." This is a matter worthy of some explanation.

X. CONTROL OF REACTORS

A reactor is controlled by "control rods," which are made of a material with a large cross section for absorbing neutrons. Inserting control rods into the reactor thus absorbs neutrons, making fewer of them available for inducing fission reactions, and thereby slowing down the chain reaction. Conversely, withdrawing control rods speeds up the chain reaction.

During steady operation, an average of 1.000 neutrons from each fission induces another fission. Suppose that some change occurs that causes an average of 1.001 neutrons from each fission to cause another fission. The number of neutrons, and hence the power level of the reactor, increases by a factor of 1.001 per generation. After 1000 generations, the power level increases by $(1.001)^{1000} = 2.7$. Since the time per generation is 10^{-4} s, the time required for 1000 generations is only 0.1 s. It is very difficult to move a massive object like a control rod very far, starting from rest, in 0.1 s. Thus we might expect frequent power excursions up and down by a factor of 2 or more. This would be an unacceptably dangerous situation.

Fortunately, something has been left out of this discussion. About 0.6% of the neutrons per fission are not emitted directly in the fission reaction, but are only emitted after the beta decay of one of the fission fragments. Since these beta decays have half lives of the order of 1 s, the neutrons emitted following them are *delayed*. Under normal operating conditions, then, an average of only 0.994 *prompt* neutrons from each fission induce another fission, and the reactor is *critical* only because of the delayed neutrons. This effectively makes the time per generation of the order of 1 s rather than 10^{-4} s, and in our above example the power increase in 0.1 s is only $(1.001)^{0.1} = 1.0001$. Consequently, power changes in a reactor normally occur very slowly. For example, starting up a reactor takes several hours as the power level increases very slowly.

However, if the control rods were withdrawn to the point where 1.007 neutrons per fission induce another fission, which means that, even discounting the delayed neutrons, 1.001 prompt neutrons per fission induce another fission, the situation reverts to our original one where the power more than doubles in 0.1 s, a highly dangerous condition called "prompt critical." A primary rule for operation of any reactor is to avoid configurations that would, under any conceivable accident sequence, lead to prompt critical conditions. This was also the rule for the Chernobyl reactor, but the operators ignored it. In their efforts to attain the desired operating level in spite of the xenon problem, control rods were withdrawn to the point where a loss of water would make the reactor very much prompt critical.

XI. THE ACCIDENT[2]

At 1:22 a.m., the feedwater flow was reduced, but since it takes some time for this to affect conditions in the reactor, control rods were not immediately reinserted.

At 1:22:30, a computer printout showed that conditions were such that the reactor should be shut down immediately. This was ignored for reasons that have not been explained.

At 1:23:04 the test was begun. Steam was diverted away from the turbogenerator, and the latter therefore began to run down. This also reduced the load on the reactor.

At this point, there were three reasons why the amount of steam in the reactor began to increase: (1) The water pumps were slowing down due to the turbogenerator rundown, thus reducing water flow. For a given heat input, less water flow means more steam. (2) The effects of the reduction in water flow at 1:22 began to have their effect. (3) The loss of load reduced the drain-off of steam.

In addition, the instability against loss of water (into steam) was having an important effect—more steam means less water, which means less poison, which means more heat generation, which means more steam—a vicious circle.

At this point, the reactor power began to increase very rapidly.

The automatic control rods went all the way in, but the power still continued to increase. At 1:23:40, the shift director ordered insertion of the emergency control rods. In Chernobyl-type reactors, the emergency control rods drop in under gravity but the "strings" to which they are attached are wrapped around a shaft that must rotate to allow the rods to fall. The downward acceleration is thus only $g/4$, rather than g as in the straight gravitational fall used in U. S. reactors. The emergency control rods got only part way in before they were blocked by damage to the reactor core.

At 1:24, two explosions were heard. Hot fragments and sparks were seen flying out of the top of the reactor building. They started about 30 fires.

It is difficult to reconstruct in any detail the sequence of events in the reactor. The tremendous heat generation undoubtedly increased the steam pressure to the point where tubes broke open. This would lead to complete loss of water which would make that region of the reactor highly prompt critical, leading to a very rapid power increase. It is estimated that the power level reached 20–100 times the normal power rating, which would generate powerful forces due to thermal expansion and vapor formation. At high temperatures, steam reacts chemically with the zirconium fuel cladding to produce hydrogen which can burn or explode if air is present. (Zirconium cladding for nuclear fuel is common in all reactor types.) With exploding fragments flying out of the building, obviously air was present. Perhaps the second of the two explosions was due to hydrogen detonation.

The most immediate problem at this point was to put out the fires, especially because there was another reactor in the same building that was in immediate danger. At about 1:30 a.m., firemen arrived from the nearby cities of Pripyat and Chernobyl, and by 3:54 a.m., the most threatening fires were out. By 5:00 a.m., all fires were out and the other reactor was shut down. Two reactors in a contiguous building continued in operation for another 20 h before receiving permission from Moscow to shut down. They were put back into operation a few months later.

The firemen displayed extraordinary heroism in putting out the fires. They received very high radiation doses, largely from radioactivity sticking to their bodies. In addition, they suffered thermal and chemical burns. Many of them later died.

At this point, there was still the problem of cooling down the reactor. The graphite was burning, and the fuel continued to generate heat from its radioactivity. Radioactive dust was spewing out. Attempts were made to pump water in, but they were unsuccessful. It was therefore decided to drop materials from helicopters into the reactor to absorb the heat and put out the fires. From 28 April to 2 May, 5000 tons of boron compounds (to assure against the reactor going critical—boron is a stong neutron absorber), dolomite, sand, clay, and lead (to melt, flow, and thus keep air out) were dropped onto the reactor. The helicopter pilots had to fly into the rising plume of radioactive dust, and many of them received heavy radiation doses that later proved fatal. As a result of their heroism, the discharge of radioactivity dropped sharply by 6 May.

In all, 31 men died, two killed outright by the explosions, and the rest from burns and radiation sickness. According to the group of Soviet physicians who toured the U. S., *none* were saved by the bone marrow transplants carried out by the visiting American physician accompanied by widespread publicity. The most serious effects, due to beta ray burns to the skin, might have been averted if they had worn the protective clothing routinely used in U. S. reactors, or if attention had been given to cleaning the exposed parts of their bodies.

While these deaths among workers at the plant were unquestionably tragic, it is perhaps worth noting that an average of close to 50 deaths occurs *every day* due to occupational accidents in the United States, and single accidents that kill more than 31 workers occur frequently in coal mines.

XII. RELEASES OF RADIOACTIVITY

Nearly all of the dangers to public health from radioactive materials released in nuclear accidents result from dispersal of airborne radioactive dust. In essentially all reactor meltdown scenarios in American LWRs, the radioactive material is released into a sealed containment building that is flooded with hundreds of thousands of gallons of water and in which water sprays containing special dissolved chemicals fill the containment atmosphere. In such a situation, the bulk of the dangerous radioactivity would become dissolved in water, and only a small fraction would be released as a radioactive dust.

In the Chernobyl reactor, on the other hand, the radioactive material was released directly into the environment as a radioactive dust, propelled upward by intense heat and the rising plume of hot gases from the burning graphite. It would be difficult to design a better system for releasing the radioactivity so as to maximize its impact on public health. Another unfortunate circumstance was that the Soviets had not been using that reactor for producing bomb grade plutonium and therefore the fuel had been in the reactor accumulating radioactivity for over two years.

The most important radioactive releases from Chernobyl were

(1) Noble gases, radioactive isotopes of krypton and xenon which are relatively abundant among the products of the fission reaction. Essentially all of these were released, but fortunately they do little harm because, when inhaled, they are promptly exhaled and do not remain in the body. They principally cause radiation exposure by external radiation from the surrounding air, and since most of their radiation is not very penetrating, their health effects are essentially negligible.

(2) Iodine-131 which has an 8-day half-life. Because it is highly volatile, it is readily released—at least 20% of the ^{131}I in the Chernobyl reactor was released to the environment. When taken into the human body by inhalation or by ingestion with food or drink, it is efficiently transferred to the thyroid gland where its radiation can cause thyroid nodules or thyroid cancers. These diseases represent a large fraction of all health effects predicted from nuclear accidents, but only a tiny fraction of these are fatal. Note that if all cases of nonfatal disease caused by air pollution from coal burning were counted, the number of health effects of electricity generation by coal burning would be tremendous.

(3) Cesium-137, which has a 30-year half-life and decays with an energetic gamma ray emission (661 keV). About 13% of the ^{137}Cs in the Chernobyl reactor was released. It does harm by depositing on the ground where its gamma radiation continues to expose those nearby for many years. It can also be picked up by plant roots and thereby get into food which leads to exposure from within the body. In either case, it can cause several types of cancer or leukemia.

In estimating radiation exposures, these three radioactive materials must be taken into account, perhaps with a small increment from others. Estimates must be made not only of the exposures received from noble gases and ^{131}I in the days immediately after the accident, but of the exposures expected from the ^{137}Cs that remains on the ground or gets into food over the next 70 years or so.

XIII. RADIATION EXPOSURES TO THE PUBLIC AND THEIR HEALTH EFFECTS

The exposures to the various groups of people who lived near the Chernobyl plant and were evacuated are listed in Table I. Note that the citizens of Pripyat, a city of 45 000 within 3 km of the plant, received much less than those further away because the radioactive dust was projected upward very high by the intense heat. We see from Table I that the most exposed group was the 16 000 people living 3–10 km from the plant with exposures of about 50 rem.

According to the most recent report of the National Academy of Sciences Committee on Biological Effects of Ionizing Radiation (BEIR),[3] the risk of fatal cancer is 1.2×10^{-4}/rem [United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR)[4] and International Commission on Radiological Protection (ICRP)[5] each estimate 1.0×10^{-4}/rem]. A dose of 50 rem therefore gives a lifetime risk of $(50\times1.2\times10^{-4} =)0.006$. If, as is typical, these people have a normal risk of 20% for dying from cancer, their exposure in the Chernobyl accident increases that risk to 20.6%. This is much less than the variation of cancer risk with geography. For example, in New England the risk is 22% vs 17% in the Rocky Mountain States.

The number of excess cancer deaths predicted among this group is $(0.006\times16\,000 =)96$, whereas the number of cancers normally expected is about $(0.2\times16\,000 =)3200$: If the latter number were known with high precision (which is highly improbable), it would have a statistical standard deviation of $(\sqrt{3200} =)\pm57$.

Table I. Estimated doses received by evacuated population.[2]

Distance away	Population	Av. dose (rem)	man-rem
< 3 km (Pripyat)	45 000	3.3	150 000
3–7 km	7 000	54	380 000
7–10 km	9 000	46	410 000
10–15 km	8 200	35	290 000
15–20 km	11 600	5.2	60 000
20–25 km	14 900	6.0	90 000
25–30 km	39 200	4.6	180 000
Total to 30 km	135 000	12	1 600 000

By very careful epidemiological studies, it may barely be possible to detect the excess of about 96 extra cancers.

Among the other 119 000 people who lived within 30 km of the plant (including citizens of Pripyat), the average exposure was only 6.7 rem, increasing each person's cancer risk from 20% to 20.08% and leading to an expected 96 extra deaths in addition to the 24 000 ± 155 normally expected. These, clearly, can never be detected epidemiologically.

The next most exposed group consists of 75 million Soviet citizens who live within about 1000 km of Chernobyl. Their estimated average eventual exposure over the next 70 years will be 0.4 rem from external radiation plus an additional 0.4 rem from eating contaminated food,[6] a total of 0.8 rem. This gives them a cancer risk of $(1.2\times 10^{-4}\times 0.8 \cong)1\times 10^{-4}$, increasing their risk from the normal 20% to 20.01%. The number of excess deaths expected is $(1\times 10^{-4}\times 75\times 10^{6} =)7500$. The great majority of expected deaths is in this group.

In Europe outside the USSR,[7] the highest average exposures were in Finland, Sweden, and sections of Germany and Poland. Eventual exposures in these areas will be perhaps 0.3 rem. In most of Western Europe, typical exposures will be more like 0.03 rem. The highest estimated exposures in the United States are 0.003 rem in Washington State. The total integrated exposure outside the Soviet Union is estimated to be 10 million man-rem, which will cause an estimated $(10\times 10^{6}\times 1.2\times 10^{-4} =)$ 1200 eventual deaths. The total number of deaths predicted from the Chernobyl accident is thus about 9000, which is roughly equal to the number of deaths from coal burning air pollution each year in the United States.

An interesting perspective on the radiation from the Chernobyl accident is obtained by comparing it with the radiation we all get from naturally occurring radon in our homes. Radon is produced continually from the decay of radium in soil, and it percolates up into houses where it is trapped to give radiation exposures. This radon is estimated to be killing about 10 000 Americans each year, equal to the total effects of Chernobyl. The average American's risk of dying from radon radiation is 0.33%, more than half of that of the 16 000 most exposed from the Chernobyl accident. About one-fourth of all Americans will get more radiation from radon than this most exposed group of Soviet citizens received from the accident.

All other groups exposed in the Chernobyl accident will receive much more exposure from radon than from the accident. The other 19 000 who lived within 30 km will receive 4 times as much from radon. The 75 million Soviet citizens who live beyond 30 km get more radiation every 2 years from radon than they got from the accident. The equivalent of the radiation from the accident is received from radon every 10 months in the high-exposure areas outside the Soviet Union, every 4 weeks in most of Western Europe, and every 3 days in the highest exposure areas of the United States.

XIV. LESSONS LEARNED AND APPLICABILITY TO U. S. REACTORS

The Soviets "learned" a great deal from the Chernobyl accident, or at least their awareness of things they already knew was heightened. They learned that instability against variations in temperature and against loss of water, which were major contributors to the accident, can be more dangerous than they had supposed. They learned that a containment structure provides an important safety guarantee if all else fails, and is therefore very useful; if the Chernobyl reactor had had an American style containment, there would have been very little release of radioactivity and hence essentially no health impacts. They learned about the efficiency of a graphite fire as a mechanism for dispersing radioactivity as an airborne dust, its most dangerous form.

They learned that experiments on reactors, involving highly abnormal operation, should not be undertaken lightly, but require very careful planning and the presence of reactor experts. They learned the importance of following rules and regulations, and not bypassing safety systems and not ignoring warnings. The performance of the operators was more like that of a frustrated physicist trying to get his homemade experiment working at 1 o'clock in the morning after a day full of delays, than like the custodians of a very large, powerful, and expensive industrial machine whose failure can cause widespread loss of life. The Soviets have recognized these lessons and have assured the World that steps are being taken to apply them, although they still insist that it is impractical to build a U.S. style containment around Chernobyl-type reactors. They have taken strong steps to improve personnel discipline in their power reactor program. Numerous officials in that program have been fired, or what they may regard as far worse, expelled from the Communist Party.

None of these lessons apply to American LWRs. They are designed to be stable against loss of water and against temperature changes under all circumstances. They have containments and do not contain graphite. Regulations are very strictly enforced. Any reactor operation with a safety system bypassed, or any ignoring of a safety warning would bring a fine of hundreds of thousands of dollars, and much more if it is not immediately reported to the Nuclear Regulatory Commission (NRC). (Every month there are stiff fines for far lesser transgressions.) Experiments using American commercial power reactors are extremely rare. They would require very elaborate justification and description of safety precautions with strict enforcement and approval from Washington.

One obvious question is why the Soviets have been so much less concerned than their Western counterparts about safety in the past. It has long been recognized that their Chernobyl-type reactors could not be licensed in the West even if they had containments, and all Western world reactors do have containments.

There has been substantial contact between Soviet and American reactor safety experts including many visits in both directions, personal friendships, lots of informal discussion over cocktails, etc. The above question has been asked and discussed many times, and the Soviet reply runs along the following lines.

The extreme concern about reactor safety in the United States has gone far beyond the bounds of rationality. With this there can be little argument. For example, new measures to improve safety introduced by the NRC in the last 12 years have increased the cost of a nuclear power plant fivefold over and above inflation, a cost increase of over $2 billion.[8] But the NRC's own Reactor Safety Study[9] estimated that, without these improvements, the average number of deaths expected due to accidents in a reactor over its estimated service lifetime is about 0.8. Thus these safety improvements correspond to spending over $2 billion per life saved ($2 billion/0.8). This is irrational for two reasons. First, there are many opportunities to save lives with cancer screening programs, highway safety measures, etc. at a cost of about $100 000 per life saved,[10] so the money spent to save one life from nuclear reactor accidents could save 20 000 lives if spent in these other areas. Second, as a result of the cost increase, utilities are forced to build coal-fired power plants instead of nuclear plants, and the air pollution from a coal-fired plant is estimated to cause at least 1000 deaths over its operating lifetime.[11] This irrational attitude toward nuclear reactor safety in the United States is therefore leading to thousands of unnecessary deaths every year, and wasting billions of dollars every year that could be used to save tens of thousands of other lives.

Why should the Soviet Union repeat this insanity? In the United States, this extreme attention to reactor safety may be unavoidable because even a minor accident could shut down the nuclear industry. The Three Mile Island accident, which killed no one and did not even come close to doing so, had a tremendous impact. That is the price we pay for our uncontrolled news media that is free to mislead the public at will. In the USSR, the media are controlled so this problem is avoided. If the Three Mile Island accident had happened in the Soviet Union, the world would never have known about it, and all the irrational consequences would have been avoided.

It is difficult to argue with the logic of the Soviet reactor safety experts, but they carried things too far. The Chernobyl-type reactor is very much more dangerous than U.S. power reactors ever were. All the differences we have pointed out apply equally to even the earliest American power reactors. If the U.S. has erred in one direction, the Soviets erred in the other. They truly gambled, and they lost.

[1] W. Meyer, S. K. Loyalka, W. E. Nelson, and R. W. Williams, Nucl. Safety 18, 427 (1927).

[2] Soviet Report on the Chernobyl Accident, English Translation. U. S. Dept. of Energy (Washington, DC), 16–17 Aug. 1986; INSAG Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident, Int. Atomic Energy Agency (Vienna), 30 Aug.–5 Sept. 1986; R. Wilson (private communication).

[3] U.S. National Academy of Sciences Committee on Biological Effects of Ionizing Radiation (BEIR), "Effects on Populations of Exposure to Low Levels of Ionizing Radiation," Washington, DC, 1980.

[4] United Nations Scientific Committee on Effects of Atomic Radiation, "Sources and Effects of Ionizing Radiation," United Nations (New York), 1977.

[5] International Commission on Radiological Protection (ICRP). *Recommendations of the International Commission on Radiological Protection*, ICRP Publication No. 26 (Pergamon, Oxford, 1977).

[6] Reference 2 gives a five times higher estimate of the eventual effects of contaminated food, based on a particular model for plant root pickup. Experience with bomb test fallout gives the figure listed here, and it represents the essentially unanimous consensus at the Vienna meeting (Aug. 1986) convened by IAEA for discussion of Ref 2.

[7] Summary report of Working Group on Assessment of Radiation Dose Commitment in Europe due to the Chernobyl accident, Bilthoven, Netherlands, 25–27 June 1986; R. Karafolios (Stone and Webster Co., Boston) (private communication); R. Wilson (Harvard University) (private communication); A. T. Ruuskanen (Finland) (private communications); H. J. M. Hansen (Denmark) (private communication); U. S. Dept. of Energy, "Assessment of the Dosimetric and Health Implications of the Chernobyl Reactor Accident," Aug. 1986.

[8] B. L. Cohen, in *Free Market Energy*, edited by S. Fred Singer (Universe, New York, 1984).

[9] U. S. Nuclear Regulatory Commission, "Reactor Safety Study," Document WASH-1400, NUREG 75/014 (1975).

[10] B. L. Cohen, Health Phys. 38, 33 (1980).

[11] R. Wilson, S. D. Colome, J. D. Spengler, and D. G. Wilson, *Health Effects of Fossil Fuel Burning* (Ballinger, Cambridge, MA, 1980). This book lists numerous other references.

Simple experiments in chaotic dynamics

Keith Briggs
Department of Physics, University of Adelaide, Adelaide, South Australia 5001

(Received 26 September 1986; accepted for publication 25 February 1987)

Five simple nonlinear physical systems exhibiting chaotic dynamics are described. They are specifically designed for demonstration purposes to illustrate the ideas of period doubling, subharmonics, noisy periodicity, and intermittent and continuous chaos.

I. INTRODUCTION

The modern concepts of chaos, period doubling, noisy periodicity, and so on are sufficiently well established to justify inclusion in the undergraduate curriculum. Indeed, several recent textbooks on dynamics[1–3] treat these ideas as an integral part of the subject, giving examples of nonlinear, chaotic systems along with the more well-known and regularly behaved systems.

Simple experiments are therefore needed to illustrate these concepts, both as lecture demonstrations and for students to investigate themselves. However, there is a basic difficulty that a student, encountering a system with chaotic dynamics, may simply view it as not working correctly,

11515 39 Ave.,
Edmonton, Alta.
T6J 0M5

2 Dec 85

TO: John Taube.
FM: Walt Fryers.
RE: Article for comments: "Nuclear Power, An American Albatross".

1. This article by Professor Thomas J. Connolly, Mechanical Engineering Dept., Stanford University, dated 1 Jul 85, is excellent. It warrants the widest possible circulation, and especially to Technocrats, many of whom have lost their objectivity on the subject, or through ignorance have been overwhelmed by fear of radiation risks and environmental hazards.

2. It would be a great mistake for Technocracy to take a doctrinaire position on nuclear matters. It is a technical subject to be handled by technical and scientific people. And, as with the broad scene of science and technology it is an area of very rapid change and development. The fears of today are overcome by the progress of tomorrow.

3. The speaker agrees that "the nuclear power enterprise has been one of the greatest managerial disasters in history". Technocrats should recognize that it constitutes an indictment of the Price System, not of the nuclear power process. The speaker further states: "The nuclear debacle represents a societal failure. Our failure. My failure and your failure." He documents the 'societal' failure very well, as far as he goes. And there he leaves it. He does not identify the basic causes of the 'failure'. He does not suggest what should be done to avoid such 'societal failure'. Too bad. A missed opportunity, in our view.

4. I am not sure just when I received the article and your note asking for comments. I just came across it. My affairs and those of the Unit have been disorganized ever since we lost our office in THE HUB at the University, and especially so since the fire that forced our move out of the Noble Bldg. The entire operation is now piled up in my garage. I hope better storage space can be arranged before long. The Unit here is totally inactive.

Walt Fryers.

P.S. I especially liked the statement: "...our adversarial system is proving a dismal failure. It produces winners and losers. It does not produce solutions."

John A. Taube
(415) 334-3733
55 CHUMASERO DRIVE #7E
SAN FRANCISCO, CA 94132

Hi, Walt:

I know you are busy, but please take a couple of minutes to drop me a short note with your comments on this article.

Cheers,

John

SECTION ON ENVIRONMENT & ENERGY Chmn: A. L. Williams
Study Section Minutes
Date: July 1, 1985

SUBJECT: "Nuclear Power, An American Albatross"

SPEAKER: Professor Thomas J. Connolly, Mechanical Engineering Dept., Stanford University

It has been said that the nuclear power enterprise has been one of the greatest managerial disasters in history--and I believe that's true. What I will discuss today, however, is not whether or not there has been a failure but, rather, who has failed. And, to get directly to the conclusion: We have failed. The nuclear debacle represents a societal failure. Our failure. My failure and your failure.

Before we look at this failure in depth, let's look at the status of uranium-based electricity in the world today.

During the post-World-War-II era, the U.S. was the leader in nuclear energy technology, today that technology has diffused widely throughout the industrialized world. The worldwide nuclear capacity exceeds 200 million kilowatts, which is the equivalent of 100 Diablo Canyon stations with its two large reactors. The United States share (13%) of nuclear power generated may look small but, in absolute numbers, the kilowatt-hours of nuclear electricity we are generating today exceeds the entire national generation back in the 1950-1955 period, just over 30 years ago.

The great bulk of the industrialized world is finding uranium-based power safe and economic. The fact that in the United States, we do not believe it is safe and are unable to produce it economically is, I submit, much more a commentary on the United States than on nuclear power technology.

The status of nuclear power plant operation and construction in the U.S. as of last February, was 88 plants licensed for operation and 42 plants in some stage of construction. In the past seven years, we have abandoned 30 plants in mid-construction, some of them nearly completed. The principal symptom of the failure I'm referring to is the huge costs of (1) some recently completed plants, (2) several of those still under construction and (3) several plants that have been abandoned after billions had sunk in their aborted construction. The capital investment in those plants that have been canceled is a dead loss. The losses nationwide, therefore, are in the tens of billions, possibly exceeding a hundred billion.

Even in the United States, however, nuclear electricity has not been a uniform economic disaster. Uranium-based electricity costs less than coal or oil-based electricity and if you postulate the absence of the nuclear plants from 1973 - 1983 and that these were replaced 75% by coal plants and 25% by oil, the same number of kilowatt-hours would have cost the nation 30 billion more dollars.

Now that I have defined the disaster, I shall proceed to the question of whose disaster. If we cannot agree that it is an economic disaster for all of us, then I'm not going to have much luck in dealing with the more difficult question of who's to blame.

Although it is probably not most important, I would first place blame on the fact that in matters of nuclear power, we have managed to scare ourselves into paralysis.

I do not want to leave the impression that ignorance about radiation effects is limited to a small group of the uneducated, however. It is an across-the-board societal phenomenon. Today's university students betray an abysmal ignorance on the subject of the health effects of radiation. Small wonder because our institutions of higher learning, my own included, have been rich sources of misinformtion on the dangers. I believe this whole phenomenon was best summarized by Davis Saxon, recent past-President of the University of California when he said that we are unable as a society to distinguish between sense and nonsense when it comes to matters of science.

Ignorance alone cannot account for our nuclear failure, however. After all, American people can hardly be more ignorant than their counterparts in nations with successful nuclear programs. So, for a more complete explanation of our nuclear debacle, I would add our failure to control (or even recognize) the excesses of the environmental movement. Between 1968 and 1978, Congress passed more regulatory statutes than it had in the previous 179 years of its history. These laws, some of them ambiguously written, provided alitigious base for the formation of a new class of environmental organization whose standard tool is litigation. I'm referring to the groups, run primarily by lawyers, such as the Environmental Defense Fund (EDF) and the Natural Resources Defense Council (NRDC). The lawyers from these organizations established great empathy with their colleagues on the benches of the Federal Courts and they were able to tie up many utilities with nuclear projects literally for years.

For a utility with as little as $100 million sunk in a project, interest charges alone are accruing at the rate of $25,000 a day. With an investment of a few hundred thousand dollars, NRDC can inflict millions of dollars of damages on an adversary. It is a very high-yeild investment. And, incidentally, it reduces our courts to instruments of political harrassment.

With respect to nuclear power and, I believe with respect to many environmental problems, our adversarial system is proving a dismal failure. It produces winners and losers. It does not produce solutions.

The legislative branch of government has also played a role in our nuclear debacle. An example of this is the government's handling of the low level radioactive waste issue.

The safe, inexpensive disposal of low-level radioactive waste is a straight forward technical problem. We are making a political mountain out of a technical molehill. What it comes down to is that a society which cannot solve that problem with dispatch is, by definition, incompetent in the area of nuclear energy.

At this point, I wish to make it clear that I realize that while I am laying the blame for the nuclear debacle on all of us, most people are laying all of the blame on the utilities and more specifically, their mismanagement. In the words of James Cook of Forbes:

> Management talent, or the lack of it, is what has made most of the difference in virtually every other nuclear project as well.

This is not an easy statement to rebut because, for one thing, there are enough authenticated cases of poor utility management across the country to provide ample support for that claim. It is just not that simple, however. I believe that the other reasons for our failure are the more important. One of these reasons is that society has made the construction of a nuclear power plant an obstacle course of Byzantine complexity, unparalleled in history. I have already referred to the ordeals by litigation. An even more serious cause of delay and, therefore, of cost overruns, has been the insistence of the Nuclear Regulatory Commission in many case that newly developed safety measures had to be incorporated into a nuclear plant even if that plant had reached a stage in its construction where the addition of that feature caused a severe disruption of the project schedule. In the management of a construction project involving anywhere from 2,000 to 7,000 workers, a schedule interruption involves expenses many times the nominal cost of the modification itself. I don't think the public in any way appreciates that fact.

In short, society, by imposing these retrofits, the endless regulations and the litigation, has made the construction of a nuclear plant an obstacle course. Even worse, it has been one in which the obstacles have been changed every few months. Clearly, some utility managers became more proficient at negotiating the courses than others. The question remains, however: Why did we have to make them such difficult courses in the first place?

This is not a defense of utility management. It is not the utlity managers, but the ratepayers and utility stockholders who must pay for the managers' errors of judgement. It will, however, be unfortunate if the book on the nuclear energy debacle is closed with the simplistic diagnosis that it was all due to poor utility management. At the present moment, that is a very tempting conclusion for many parties. It relieves so many of them, the courts, the Congress, the NRC, the antinuclear environmental groups, of responsibility. For the consumer groups, who will

be asking the utility comissions to disallow much of the nuclear plant costs for rate-setting purposes, the utility mis-management story is a godsend. After all, one can hardly assess the courts or the Natural Resources Defense Council for their share in high nuclear electricity costs.

There really isn't much question but that the electricity consumer must ultimately pay for the nuclear plants. More difficult are the questions: Does the U.S. need any more nuclear plants than it now has under construction? If so, can the U.S. actually build them? To answer the first question, lets look at energy consumption in the U.S. from 1973 to 1984. While our total energy consumption was essentially the same last year as it was in 1973, electricity production rose 31%. Non-electric energy uses, primarily transportation, declined 12%. This shows a marked shift toward electricity which hasn't shown any sign of slackening. Moreover, it is probably the kind of a shift one would expect in an industrialized nation with relatively high labor costs. Even though there is no shortage of electricity production facilities in the U.S. today, it would seem imprudent in the extreme to take nuclear technology off the menu of options. The situation can vary widely from one utility to another and from one region of the country to another. Whether we ever add another nuclear plant to the nation's electric capacity, however, it is hardly wise for a society so dependent as ours on electricity to be sending a message to electric utilities that they invest in innovative generating technologies at their own risk. A cost-regulated, risk-taking utility is a contradiction in terms. What we can expect from our present policy, therefore, is underinvestment inefficient new electric generating capacity.

In Coleridge's story of the ancient mariner, the principal character was a member of the crew of a sailing vessel. One day, for no apparent reason, the sailor shot an albatross that had been flying along with the ship for some time. The fortunes of the voyage immediately took a turn for the worse. His shipmates turned on the sailor. They attributed their bad luck to the shooting of the albatross. So they took the dead bird and hung it around the sailor's neck.

I hope it isn't forcing the allegory too far to suggest that we have shot the nuclear albatross. It is around our necks because we, either as electric consumers, utility stockholders, or taxpayers, must pay the billions represented by the nuclear plants abandoned in mid-construction or the billions in excess costs of the completed plants. It is we, the public, who must pay for the regulatory bureaucracy and for the disposal of nuclear wastes at costs made ten times what they should be because of our adversarial approach to problem solving. All of these costs the public must bear while being denied the compensating benefits, because we have removed nuclear technology from the menu of options the electric utilities have in expanding and modernizing their generating plants. In short, nuclear power is an albatross on the American public's neck because the public must bear its costs while being denied its potential benefits.

RESPECTFULLY SUBMITTED,
ROBERT E. SCHIFFNER

7
[illegible]

[redacted]
We're the furniture people.
[redacted]

From: John A. Taube
(415) 334-3733
55 CHUMASERO DRIVE #7E
SAN FRANCISCO, CA 94132

FIRST CLASS MAIL

SAN FRA[illegible] CA US PS
OCT-8'86
U.S. POSTAGE
0.50

To: Walt Fryers
11515 39 Ave
Edmonton, Alta.
T6J 0M5
Canada

Walt'
Let me know what you
think?

FIRST CLASS MAIL

FIRST CLASS

EDITED AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

TechnologyReview

The Trouble with Fusion

BY LAWRENCE M. LIDSKY

ILLUSTRATION: JANE BIANCO

The technically advanced nations of the world will spend over $1 billion this year in the quest for controlled thermonuclear fusion power. This program has been sustained for 30 years with steadily mounting commitments of money and the dedication of an international group of scientists and engineers. Our knowledge of the related physics has grown enormously in the effort. Now the solution of the scientific problem appears to be almost within our grasp, and many assume that with it will come that technological Holy Grail: virtually unlimited, environmentally safe energy. But that outcome is unlikely. Instead, the costly fusion reactor is in danger of joining the ranks of other technical "triumphs" such as the zeppelin, the supersonic transport, and the fission breeder reactor that turned out to be unwanted and unused.

The dominating goal of the fusion program is to produce a reactor fueled by deuterium and tritium, isotopes of hydrogen containing one and two extra neutrons. This choice of fuel greatly eases the problem of achieving an energy-producing fusion reac-

Long touted as an inexhaustible energy source for the next century, fusion as it is now being developed will almost certainly be too expensive and unreliable for commercial use.

tion, but the choice also has features that make it far more difficult to turn that energy source into a useful power plant. The most serious difficulty concerns the very high energy neutrons released in the deuterium-tritium (D-T) reaction. These uncharged nuclear particles damage the reactor structure and make it radioactive. A chain of undesirable effects ensures that any reactor employing D-T fusion will be a large, complex, expensive, and unreliable source of power. That is hardly preferable to present-day fission reactors, much less the improved fission reactors that are almost sure to come.

Scientists routinely fill vacuums with ionized gases, or plasmas, at temperatures of tens of millions of degrees Centigrade (above). To achieve a sustained fusion reaction, scientists at the Princeton Plasma Physics Laboratory plan to heat plasma inside this vacuum vessel (right) to temperatures 20 million degrees hotter than have so far been achieved.

When these drawbacks become more widely realized, disillusionment with the existing fusion program will weaken the prospects for other fusion programs, no matter how wisely redirected, for decades to come. But such a result isn't necessary. The public has shown that it is enlightened enough to support long-range scientific research without a clearly defined near-term goal; witness the support for expensive research on high-energy physics. Furthermore, other nuclear reactions such as the fusion of protons with lithium or boron produce either fewer neutrons or none at all. A reactor based on these fuels would be far preferable to existing fission reactors.

Of course, we do not know how to build a reactor to ignite such "advanced" fuels. Indeed, we know that neutron-free reactions cannot be ignited in the magnetic bottles developed for D-T and, unfortunately, little of the physics painstakingly developed for D-T fusion will apply. There is no clear path for an alternative scheme, and not coincidentally almost no support. As a result, only a few researchers are at work in the field. But it is clear that if we can build a reactor employing neutron-free fuels, we can avoid the enormous, probably insurmountable, problems posed by deuterium and tritium.

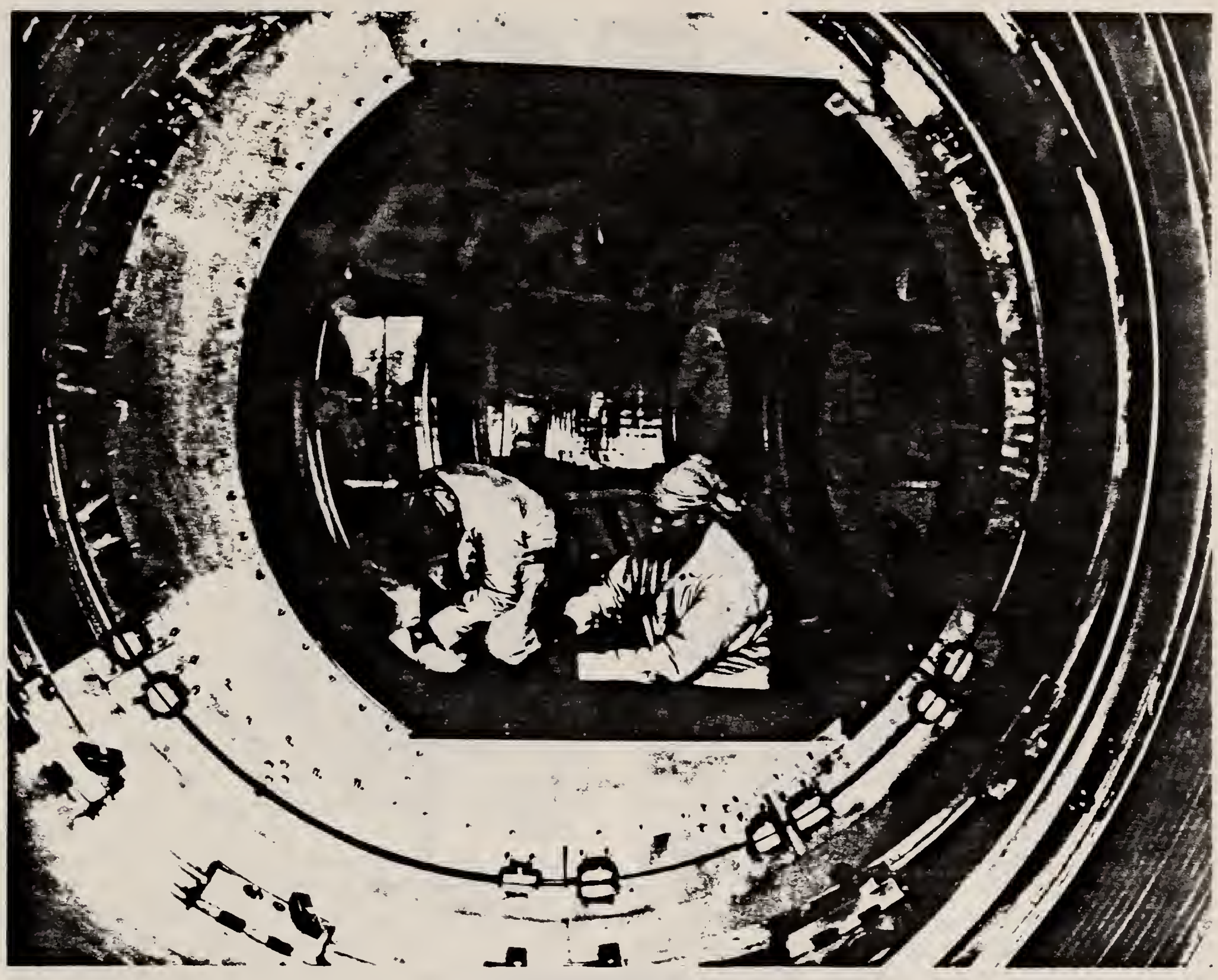
How could highly motivated and intelligent people get themselves into such a difficult situation? A fundamental reason concerns the difference between scientists' and engineers' view of what it means to solve a problem. Although they are usually able to agree on the definition of a "good problem," scientists and engineers often have different perspectives as to what constitutes a "good answer."

Good problems challenge our abilities to the limit but ultimately are solvable—that is, they are not so difficult that the time spent is wasted. In both science and engineering, the greatest satisfaction accrues to those solving a problem first, even though "better" (simpler or more complete) answers are often found later. In science, such answers can coexist peacefully and are usually mutually illuminating. However, engineering answers must meet economic and social demands from the start, and fundamentally different answers rarely coexist for long.

Fusion is a textbook example of a good problem for both scientists and engineers. Many regard it as the hardest scientific and technical problem ever tackled, yet it is nonetheless yielding to our efforts. We have made substantial scientific progress, and the advances in fusion-system engineering have been astounding. We have developed superconducting magnets that dwarf ordinary laboratory magnets. Today's particle beams are nearly a million times more powerful than those available at the beginning of the program. We routinely fill huge devices with ionized gases at temperatures of tens of millions of degrees and use lasers to measure their properties. The fusion program has stretched our abilities to the utmost, and we have responded.

The fusion program was, from its inception, dominated by scientists. In the best tradition of science, we chose the most promising target—D-T fusion—out of the dauntingly complex areas of thermonuclear physics, and we concentrated on it. We may well achieve that goal, which would be a scientific triumph. But the scientific goal turns out to be an engineering albatross. From the engineering point of view, we should have started from the answer and worked backward.

The second reason why intelligent and motivated people were led astray in fusion research is common to government programs that must compete annually for funds. There is a strong temptation to choose a near-term answer over a more rational long-term answer, even though this choice precludes reaching the



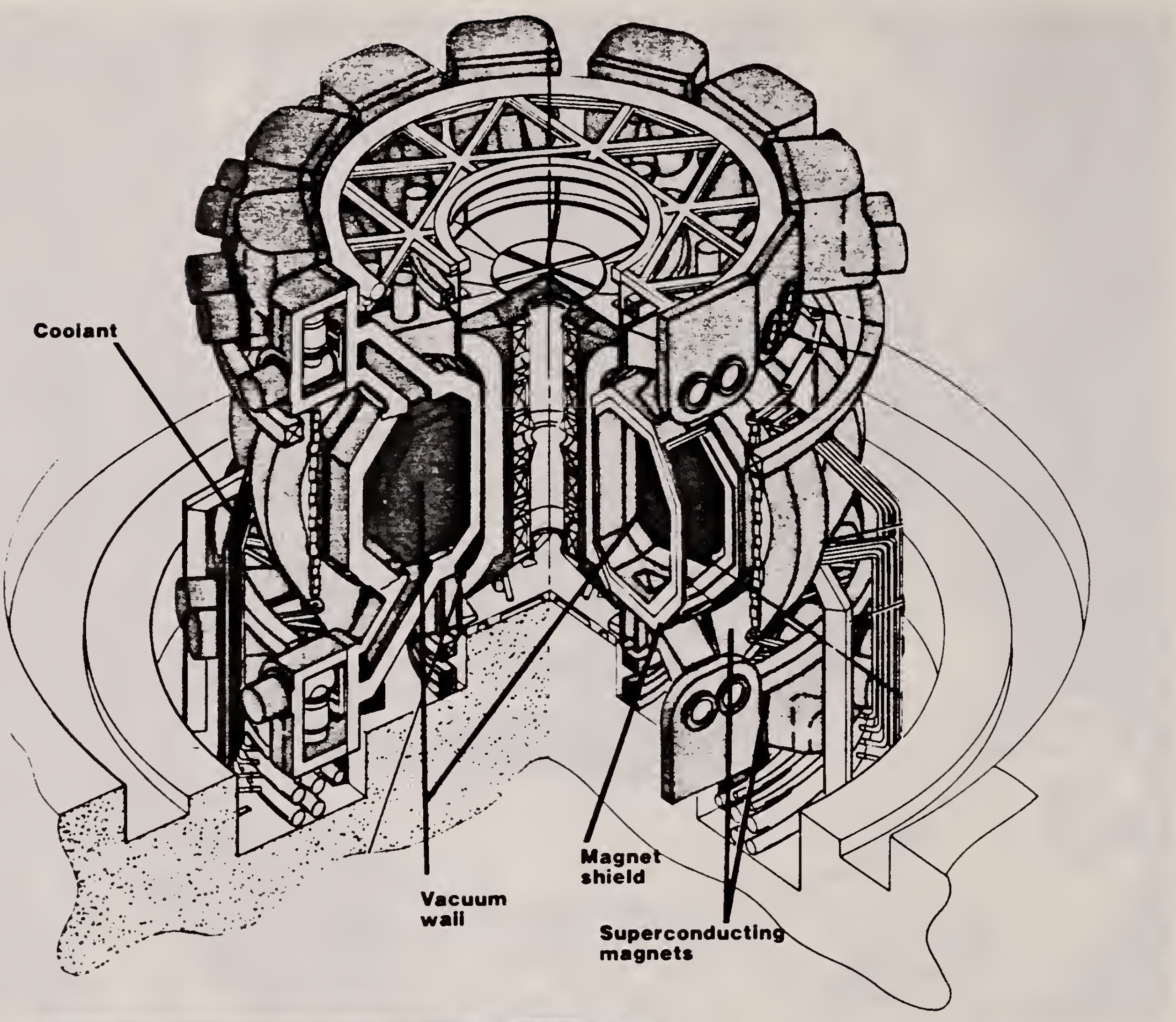
ultimate goal. The alternative would be the much more difficult task of developing support for a long-range program through persuasion and education. There is a related disinclination to adjust established plans, even if perceptions change. Indeed, it is considered dangerous even to admit uncertainty in a highly visible public program. Once established, an explicit goal, such as generating commercially competitive electricity from D-T fusion, is not easy to change.

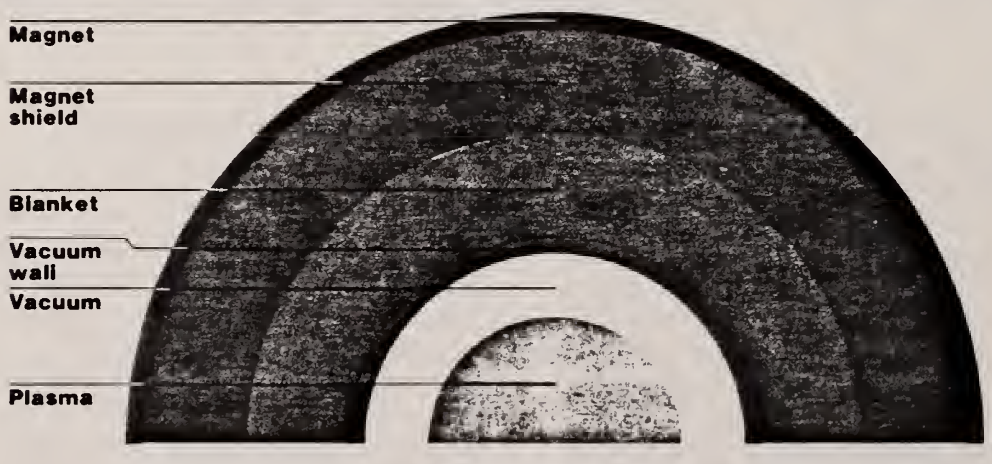
As a result, the Office of Fusion Energy of the U.S. Department of Energy has promised that it will, early in the next century, demonstrate the production of large amounts of power via D-T fusion. Producing net power from fusion is a valid scientific goal, but generating electricity commercially is an engineering problem. The requirement is to develop a power source significantly better than those that exist today, and D-T fusion cannot provide that solution. Even if the fusion program produces a reactor, no one will want it.

The Science of Fission and Fusion

Fusion and fission power both have their roots in nature's tendency to favor the nuclear moderate: the elements of intermediate weight are energetically preferred—that is, the elementary particles forming the nucelus are more tightly bound. As a result, energy can be released either when heavy nuclei are split (fission) or light nuclei are joined (fusion). Fission is far easier to achieve than fusion. Several atoms with heavy nuclei, such as uranium-235 and plutonium-239, are on the verge of splitting spontaneously; adding a single nuclear particle causes instantaneous fission. The nucleus splits into smaller fragments, releasing energy and several neutrons. These neutrons, because they are electrically neutral, can easily penetrate the electric barriers surrounding uranium and plutonium nuclei to cause additional fissions. This, of course, is the so-called "chain reaction."

PHOTOGRAPHS: PRINCETON PLASMA PHYSICS LABORATORY





The schematic cross-section of proposed fusion reactors (bottom) has remained essentially unchanged from one proposed in a 1961 textbook. In the most likely scheme, called the "tokamak" (top), the tubular reactor is curved to form a torus (or doughnut).

Temperatures in the plasma where fusion takes place would approach 150,000,000° C. The inner surface of the vacuum (or first) wall (pink) encircling the plasma will be subjected to intense heat and bombardment by damaging neutrons from the reaction. The "blanket" containing lithium, outside the first wall, absorbs these neutrons to "breed" tritium for fuel. The engineering will be complicated by the fact that lithium reacts explosively with air and water.

On the reactor's exterior, the superconducting magnets that contain the plasma must be cooled almost to absolute zero. Hence the shielding to protect them from the extreme heat.

Despite the potential for problems in such a reactor, hands-on repair will be impossible because of radioactivity. All in all, the proposed fusion reactor would be a large, complex, and unreliable way of turning water into steam.

DIAGRAMS: OMNIGRAPHICS

Temperatures within a fusion reactor will range from the highest produced on earth to almost the lowest possible.

The problems with fission almost all stem from the smaller fragments of the original nucleus. We have no control over which of the hundreds of different fission products are formed, and, unfortunately, many are noxious, radioactive, toxic, or corrosive. These fission products are primarily responsible for the problems of reactor safety, including waste disposal and even the possibility of a meltdown.

Although fusion is conceptually simpler than fission, it is technically much more demanding. The root of the problem is that there is apparently no equivalent of the fission reaction that is induced by uncharged neutrons. All the nuclei that must be brought together for fusion are positively charged and, therefore, repel each another. This repulsive force between nuclei increases rapidly with increased atomic charge and becomes prohibitive for even moderately large atoms. Thus, it appears that fusion fuels must be chosen from among the lightest elements—hydrogen, helium, lithium, beryllium, and boron. But despite the relatively small number of light elements, more than 100 fusion reactions are possible.

Common to all is the fact that the reacting particles must be raised to very high energies (that is, must be very hot) to overcome their mutual electrical repulsion and approach close enough to fuse. Even at these very high energies, the particles are much more likely to bounce off each other at random angles—to "scatter"—than to fuse. Energy is conducted out of the system in this process. Thus, energy must be used to ignite fusion and to replace the energy continuously lost by the hot fuel. Obviously, the energy produced by the reaction must exceed the required input if the reactor is to be of any use.

But merely producing a net positive power output is not enough; achieving a high enough power *density* is also crucial. Power density refers to the rate of energy production per unit of reactor volume. Fusion will almost certainly have a lower power density than fission and therefore will require a larger plant to produce the same output. Suppose a fusion plant had to be ten times as big—and therefore likely ten times as costly—as a present-day fission plant to produce the same amount of power. Given the already intolerable costs of building fission plants, that would hardly be economically feasible. These issues of producing net energy and achieving a high enough power density are the dominant themes of fusion.

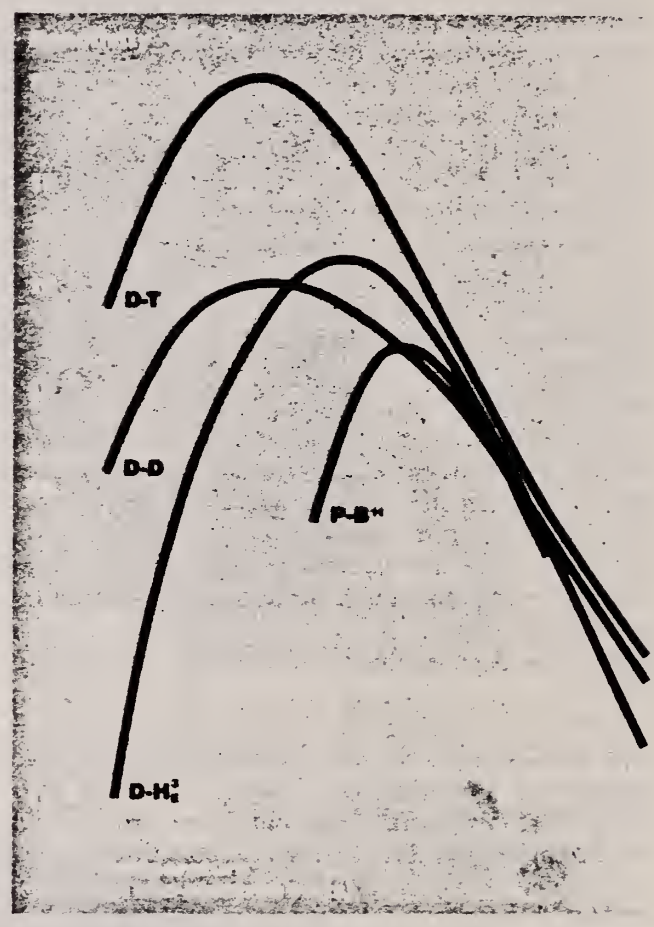
How Fusion Fuels Work

The choice of deuterium and tritium as fuels early in the fusion program evolved quite naturally. Deuterium is a nonradioactive isotope of hydrogen that, as mentioned, has one extra neutron in the nucleus. In nature approximately 1 out of every 6,500 hydrogen atoms is deuterium. Thus, it is abundant—after all, there is a lot of hydrogen in seawater—and separating it from ordinary hydrogen is straightforward because of the substantial disparity in the masses.

The first reaction seriously considered for fusion power plants was simply the self-fusion of deuterium—the D-D reaction. Deuterium reacts with itself to produce either helium-3, a stable but extremely rare isotope of helium, or tritium, the triply heavy isotope of hydrogen with two extra neutrons in the nucleus. These reaction products can themselves react with deuterium to produce even more energy than comes from the D-D reaction itself. Thus, a deuterium-fueled fusion reactor could, and almost certainly would, recycle and burn both the tritium and helium-3 in the so-called D-T and D-He^3 reactions.

Calculating the energy available from this complex series of reactions is the first problem assigned to students in my introductory course in controlled fusion at M.I.T. If they do their work properly, the students find out that the energy released by fusing the deuterium in one cubic meter of seawater equals that released by burning 2,000 barrels of crude oil. Every single cubic kilometer of ocean water therefore contains as much energy as the world's entire known oil reserves, and there are more than a billion cubic kilometers of water in the oceans. This astounding finding—in effect, an inexhaustible source of energy—shows why tens of billions of dollars have been spent and hundreds of scientists have devoted their entire careers seeking to tap this extraordinary energy source.

Unfortunately, making D-D reactions occur is extraordinarily hard, but there is an alternative. The tritium by-product that would be recycled in the D-D reactor is a far better fuel when mixed with deuterium than is deuterium itself. Not only is more energy released, but the combination of deuterium and tritium is 100 times more reactive than a simple mixture of deuterium. In other words, in similarly



The fusion of deuterium (D) with tritium (T) is 100 to 1,000 times more reactive than the fusion of combinations involving helium-3 (He^3), protons (p), or boron-11 (B^{11}). In other words, a D-T-based power plant would yield 100 to 1,000 times more energy than an identical plant using the other fuels. That is why almost all research has focused on D-T fusion. However, the energetic neutrons it releases would damage and induce radioactivity in the reactor structure.

engineered reactors, a system fueled with deuterium and tritium will produce at least 100 times as much energy as one fueled by deuterium alone. Thus, as soon as scientists realized how difficult fusion was to achieve, they almost unanimously agreed that developing the D-T reactor should be the first goal of the fusion program. This scientific goal was well justified, and no one seriously questioned it as an engineering goal at the time.

One of the first issues posed by the D-T fusion reaction was how to supply sufficient tritium. Tritium is radioactive, with a relatively short half-life of 12.4 years, and therefore it exists only in minute quantities in nature. Luckily, the neutron emitted in D-T fusion can react with an isotope of lithium to produce tritium and even release additional energy in the process. Though nothing compares with the vast store of deuterium in seawater, the world's lithium resources are enough for several thousand years of energy production. The lithium-neutron reaction resolves the tritium-supply problem. However, it introduces additional engineering difficulties.

Fusion Reactors: Large and Complex

The severity of the technical problems associated with the D-T reaction was not fully understood in the early years of the fusion program. But these difficulties have gradually been revealed by the extraordinarily detailed series of conceptual reactor designs produced under Department of Energy (DOE) funding over the last decade. The object of these studies is to describe a plausible fusion reactor based on the underlying physics and reasonable extrapolations of the technology. Of course, no one can be certain exactly what a D-T fusion reactor will look like. Nevertheless, several difficult questions that might seem to depend on this knowledge can already be answered. In particular: will a fusion reactor be simpler or more complex, cheaper or more expensive, safer or more dangerous, than a fission reactor? The answers depend only on the broad outlines of future reactors.

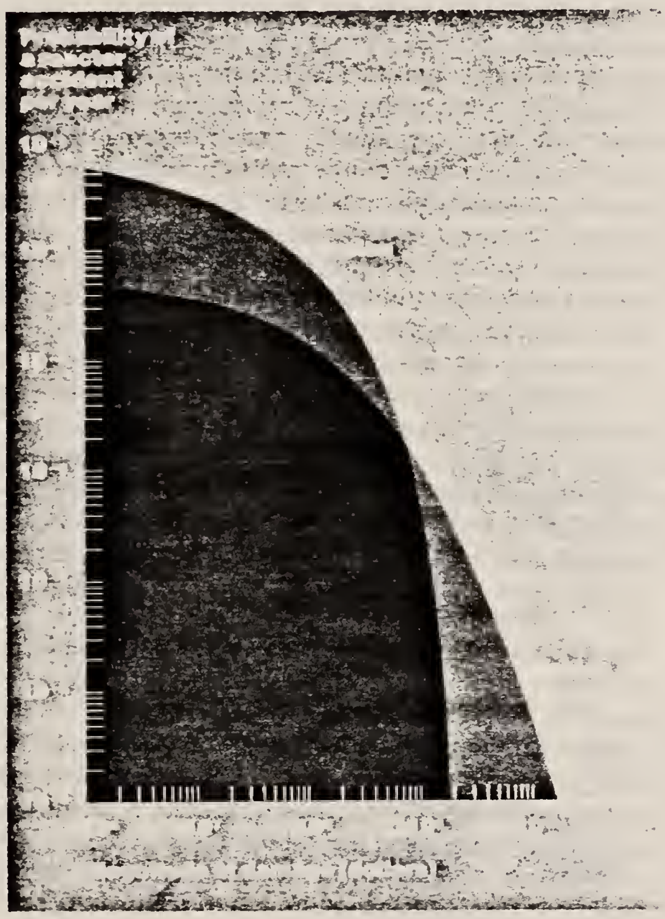
The main fusion reaction will take place in a gas-like plasma in which deuterium and tritium atoms are so energetic—so hot—that the nuclei have lost their electrons. The temperature of this gas will probably exceed 150,000,000° C. This plasma cannot be contained by physical walls, not only because no material could withstand the heat, but also because walls would contaminate the plasma. Instead, the plasma will be bottled within a vacuum by magnetic forces.

Four-fifths of the energy from the D-T reaction is released in the form of fast-moving neutrons. These neutrons are 15 to 30 times more energetic than those released in fission reactions. The first wall surrounding the plasma and vacuum region will take the brunt of both the neutron bombardment and the electromagnetic radiation from the hot plasma. This first wall is expected to be made of stainless steel or, better, one of the refractory metals such as molybdenum or vanadium that retain their strength at very high temperatures.

In colliding with this wall, the neutrons will give up some of their energy as heat. This heat must be removed by rapidly circulating coolant to prevent the wall from melting. After being piped out of the reactor, the heated coolant is used to produce steam and generate electricity.

Many of the collisions between neutrons and atoms in the first wall actually knock the atoms form-

The worst possible accident for a fusion reactor would destroy only the power plant itself—a minor hazard compared with the possibility of a meltdown in a fission reactor. However, a fusion reactor would be far more complex and prone to minor accidents. Since the fusion reactor would be too radioactive for hands-on repair, any accident could pose grave financial consequences for utilities. (The general shapes in the diagram are correct; however, the actual numerical values are uncertain and should not be taken literally.)



ing the metal out of their original positions. Each atom in the first wall will, on average, be dislodged from its lattice position about 30 times per year. Obviously, this causes the structure of the metal to deteriorate.

A few of the neutrons colliding with atoms in the first wall will have the beneficial effect of dislodging some neutrons from the atomic nuclei. These dislodged neutrons, plus the original ones generated by the fusion, pass through the wall and into the so-called "blanket," which contains lithium in some form. Here, the bulk of their energy is used to produce heat, which also is used to create steam for generating electricity, and eventually the neutrons are absorbed by the lithium to "breed" tritium.

Lithium itself poses serious engineering problems. It is an extremely reactive chemical: it burns violently when it comes in contact with either air or water and is even capable of undergoing combustion with the water contained in concrete. The lithium may be either in liquid form or in a solid compound. Liquid lithium blankets produce substantially more tritium and allow it to be more easily removed. However, the need to handle large amounts of this metal in liquid form leads to technical complexity and poses safety hazards.

The tritium-breeding region has other engineering requirements. It must be designed in such a way that the structural materials, as contrasted with the actual lithium, capture a minimum of neutrons. Also, the operating temperature must be high enough so that the coolant, when piped outside the reactor, can generate steam efficiently.

Outside the blanket, powerful magnets must provide the magnetic fields to contain the plasma. These fields will exert enormous forces on the magnets themselves, equivalent to pressures of hundreds of atmospheres. If made from copper wire, these magnets would consume more power than produced by the reactor, so they will have to be superconducting. Superconducting magnets, cooled by liquid helium to within a few degrees of absolute zero, will be extremely sensitive to heat and radiation damage. Thus, they must be effectively shielded from the heat and radiation of the plasma and blanket.

Temperatures within the fusion reactor will range from the highest produced on earth (within the plasma) to practically the lowest possible (within the magnets). The entire structure will be bombarded with neutrons that induce radiation and cause serious damage to materials. Problems associated with the inflammable lithium must be managed. Advanced materials will have to endure tremendous stress from temperature extremes and damaging neutrons. The magnetic fields will exert forces equivalent to those seen only in very high pressure chemical reactors and specialized laboratory equipment. All in all, the engineering will be extremely complex.

A working fusion reactor would also have to be very large. This conclusion is based on fundamental principles of plasma physics and fusion technology. To begin with, because of the properties of magnetic fields, a fusion reactor must be tubular. There is still dispute as to whether this tube should be bent into a toroidal (doughnut) shape, as in the device known as the "tokamak," or kept as a long, straight tube with end plugs, as in the device known as the "tandem mirror." However, the main conclusions as to the size and complexity of a D-T reactor are independent of this choice.

A fusion reactor might well produce only one-tenth as much power as a fission reactor of the same size.

The first wall of the reactor encloses the plasma. The best theories available suggest that the radius of the plasma must be at least two to three meters if the fusion reaction is to be self-sustaining. Even if a breakthrough in physics were to allow a smaller plasma, separate engineering requirements would prevent the radius of the first wall from being appreciably less than three meters. These requirements arise from the need to avoid excessive differences in power density.

For the neutrons to be slowed enough in the lithium to effectively breed tritium, the blanket surrounding the first wall must be between half a meter and one meter thick. The radiation shield outside the blanket must also be between half a meter and one meter thick to protect the supercooled magnets. Finally, the superconducting magnets and their structure will add another meter each to the radius. That gives a total radius of at least five meters for the plasma and the tube surrounding it.

In a tokamak reactor, this tube—over 30 feet across—would be bent into a doughnut-like shape at least 75 feet in outer diameter. As a power plant, this is somewhat larger than today's fission reactors and substantially more complex. If the energy density of the fusion plant turned out to be lower than that of a contemporary fission plant, as seems likely, then all this size and complexity would produce less power—hardly an economic proposition. But even if the power density were comparable, the D-T fusion reactor would, like today's fission plants, be a large and costly power source, producing thousands of megawatts of electricity. Detailed studies, some costing millions of dollars, aimed at deducing the smallest plausible size for a D-T fusion reactor all come to this same discouraging conclusion.

Such a large reactor would not meet the needs of utilities. Plagued by financially crippling cost overruns on fission reactors, managers are loathe to invest several billion dollars in any single plant, fission or fusion. Smaller plants, such as coal plants with scrubbers, are much easier to finance, not only because the investment is far lower, but also because the final cost is predictable. And if a small plant breaks down, the effects on regional electricity production are much less serious. Thus, utility managers find large plants undesirable.

Suppose fusion reactors could be built despite the inherent difficulties of size and complexity. Another critical engineering problem would still have to be faced. That is the matter of heat transfer—the way in which heat is removed from the reactor structure by the circulating coolant. The history of much large-scale power engineering has been dominated by the effort to achieve ever higher temperatures and heat-transfer rates. High temperatures imply high efficiency, and high heat-transfer rates imply high power density. Because these goals are so desirable, heat-transfer systems have been pushed close to their limits. Above these limits, materials either melt or fail from excessive stress caused by heat. Additional gains are coming only slowly.

Consider heat transfer in fission and fusion reactors. In today's typical light-water reactor (LWR), heat is generated by fission in fuel pins containing uranium. The heat is then transferred to the coolant at the surfaces of a relatively large number of small-diameter pins. This arrangement provides a larger surface area to transfer heat than, say, a single large fuel cylinder. Indeed, by decreasing the diameter of the pins even further (but increasing their number to keep the amount of uranium unchanged), the total surface area available to transfer heat would be further increased. Thus, the actual heat-transfer rate through any given square inch of surface on a fuel rod is not critical. Sufficient heat can always be removed merely by increasing the total area.

This strategy does not work in a fusion reactor. The heat-transfer surface is limited to the inside of the wall surrounding the plasma, and the relatively small surface area of this wall cannot be increased without further increasing the size of the reactor. In fact, bigger reactors need *larger* heat-transfer rates. Thus, the actual heat-transfer rate per square inch must be extremely large and cannot simply be reduced by a design change.

Suppose a fission reactor and a fusion reactor were built with equivalent heat-transfer rates. Knowing this, one can calculate two other critical engineering factors: the flux of neutrons at the heat-transfer surface, and the overall power density of the reactor. The neutron flux should, of course, be as low as possible, because it damages the reactor structure and makes it radioactive. And the power density should, as mentioned, be as high as possible, so that a reasonable amount of power will be produced in a reactor of a given size.

On these counts, a comparison between current LWR fission reactors and the somewhat optimistic fusion designs produced by the DOE studies yields a

The drawbacks of the existing fusion program will weaken the prospects for other fusion programs, no matter how wisely redirected.

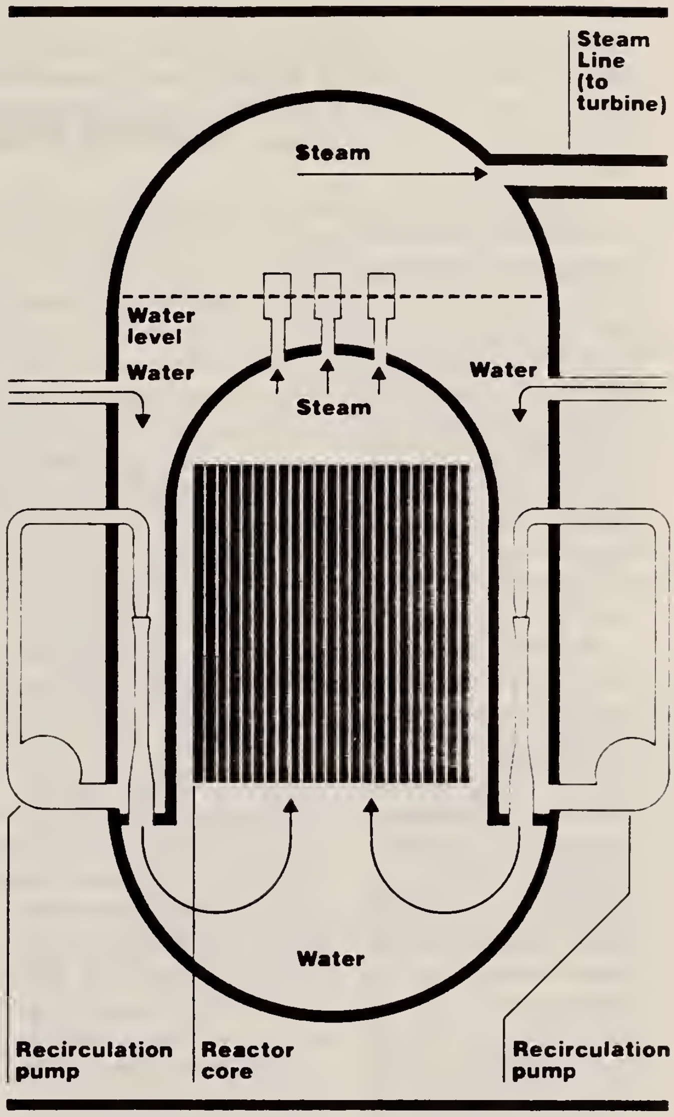
devastating critique of fusion. For equal heat-transfer rates, the critical inner wall of the fusion reactor is subject to ten times greater neutron flux than the fuel in a fission reactor. Worse, the neutrons striking the first wall of the fusion reactor are far more energetic—and thus more damaging—than those encountered by components of fission reactors. Even in fission reactors, the lifetimes of both the replaceable fuel rods and the reactor structure itself are limited because of neutron damage. And the fuel rods in a fission reactor are far easier to replace than the first wall of the fusion reactor, a major structural component.

But even though radiation damage rates and heat-transfer requirements are much more severe in a fusion reactor, the power density is only *one-tenth* as large. This is a strong indication that fusion would be substantially more expensive than fission because, to put it simply, greater effort would be required to produce less power.

Fusion's Benefits

Given all of fusion's liabilities, why are we working so hard on it? The universal availability of fuel has provided a strong motive to develop fusion, and it does promise some other substantial advantages over fission. To begin with, fusion generates much less radioactivity than fission, and there is no long-term storage problem for radioactive wastes. A fusion reactor would create a lot of tritium, which is radioactive and hard to contain. However, tritium's biological effects are relatively benign—it does not tend either to concentrate or to linger in living organisms—and it emits relatively weak radiation. After a short period of operation, the radioactivity from neutrons bombarding the structure of a fusion reactor itself would greatly exceed the feeble radioactivity of the tritium.

But even the radioactivity of the structure will be composed primarily of nonvolatile isotopes. By contrast, a substantial amount of the radioactivity in fission reactors is in the form of volatile gases that can escape if the containment structure is breeched. To further minimize the radioactivity associated with fusion, reactor designers can choose structural materials that do not become strongly radioactive when bombarded by neutrons. A fusion reactor of stainless steel would have 300 times less radioactivity than a fission reactor of the same power output. A fusion



In a fission reactor, heat from the reaction is released through the surfaces of thousands of fuel rods. Additional surface area to transfer heat can be created by providing more fuel rods but making them thinner.

However, in fusion plants, the 150,000,000° C plasma is encircled by a "first wall," the surface of which cannot be increased in any practical way. (If the encircling wall is made bigger, then the larger plasma creates even more heat.) Thus, as much energy as possible must be transferred through each square inch of the first wall. Unfortunately, improvements in heat-transfer rates are coming only slowly.

Neutrons induce radioactivity and damage reactors. Neutron-free fusion might provide inexhaustible, benign power.

reactor based on a vanadium structure would be 10 times better yet. In other words, it seems possible to build a fusion reactor with 3,000 times less radioactivity than a fission reactor producing the same amount of power.

The radiological difference between fission and fusion is even more striking in the production of long-lived wastes. There is nothing in the fusion reactor comparable to the fission fragments or the plutonium in fission reactors. Plutonium is extremely hazardous and its radioactivity is very long-lived, with a half-life of 24,100 years. After a 100-year storage period, the radioactive waste produced by a stainless-steel fusion reactor would be 1 million times less hazardous than that produced by an equivalent fission reactor. And there would be no need to store the waste of a fusion reactor with a vanadium structure even that long. A well-designed fusion reactor could completely eliminate the problem of storing long-term waste.

The fact that a fusion reactor does not require long-term waste storage seems a clear advantage. But it is less significant than would first appear, for we have tended to exaggerate the waste-storage problems of fission reactors, primarily because of ill-considered decisions early in their development. Early schemes for disposal of fission wastes had to be inexpensive to allow the reactors to compete with conventional power plants fueled by inexpensive oil. Early schemes for disposing of the wastes—dumping them on the ocean bottom or injecting them into underground strata—were certainly cheap. However, these schemes were so clearly inadequate that the fission community did its reputation lasting damage by advocating them.

Although the public is still concerned about the disposal of radioactive waste, the economic situation is now completely changed. Fission products can be safely stored, as is routinely done in Europe now. To be sure, such processes are not inexpensive. For example, one technique consists of sealing intact fuel elements in welded metallic canisters and storing them in mined granite cavities. If better techniques for storage should become available, the wastes can be retrieved. The costs of such relatively expensive disposal still play only a small role—less than 10 percent—in the total price of power. Public perception changes slowly, but the time scale under consideration is long. Waste disposal will eventually be considered a difficult but not insurmountable problem.

The matter of safety is difficult to weigh so concretely. Current analyses show that the probability of a minor mishap is relatively high in both fission and fusion plants, because both contain many complex systems. But the probability of small accidents is expected to be higher in fusion reactors. There are two reasons for this. First, fusion reactors will be much more complex devices than fission reactors. In addition to heat-transfer and control systems, they will utilize magnetic fields, high power heating systems, complex vacuum systems, and other mechanisms that have no counterpart in fission reactors. Furthermore, they will be subject to higher stresses than fission machines because of the greater neutron damage and higher temperature gradients. Minor failures seem certain to occur more frequently.

Comparing the probability of more serious accidents is harder, partly because that issue is the subject of such heated debate concerning fission reactors. But the probability of major accidents affecting public safety will certainly be substantially lower for fusion reactors. Indeed, the hypothetical worst-case accident of a fission reactor—catastrophic meltdown with release of fission products—has no equivalent in fusion. The fusion reactor simply does not contain enough radioactive material.

Thus, fusion reactors will have a higher probability of small accidents but a much lower probability of major accidents. This at first appears to be a strong argument for fusion, but consider Three-Mile Island. This accident, thought by some to have sounded a death knell for the fission industry, may have had equally damaging consequences for fusion. Although no one was physically injured in the TMI accident, the utility owning the reactor was mortally wounded financially. The multi-billion-dollar plant was put out of commission because it was too radioactive to repair. From a manager's standpoint, all systems that are too radioactive for hands-on maintenance are equivalent: if something major breaks, it is unrepairable. Although there is much less radioactivity in a D-T fusion reactor than in a fission reactor, it is still so high that contact maintenance would be impossible. And a D-T fusion reactor would be far more likely than a fission reactor to require repairs.

The analysis of safety factors comes down to this: While the public is primarily concerned about major catastrophes, power-plant operators are also fearful of less threatening accidents that could cause serious financial problems. In respect to these, fusion is at a

Neutron-Free Fusion

Almost all of the lighter elements are capable of entering into fusion reactions in which the nuclei of atoms are combined and energy is released. The prime candidates for power-producing reactions are based on two isotopes of hydrogen: protons (p), which are the standard hydrogen nuclei; and "heavy hydrogen," or deuterium (D), which has a neutron attached to the proton. The nuclei of the hydrogen isotopes have the lowest possible electric charge—one positive charge. Thus, they require lower energies to be brought together for fusion reactions than other nuclei with larger positive charges.

The original proposal for fusion was to produce power through the self-fusion of deuterium—the D-D reaction. This reaction produces, with equal probability, either the light helium isotope with two protons and a neutron (He^3) or the heaviest hydrogen isotope, tritium (T), with one proton and two neutrons. Both reactions release energy, generally measured in millions of electron volts (MeV).

$$D + D \rightarrow He^3 + n + 3.2\ MeV$$

$$D + D \rightarrow T + p + 4.0\ MeV$$

These reaction products can themselves react with deuterium and will either be "burned" in place or recycled.

$$D + T \rightarrow He^4 + n + 17.6\ MeV$$

$$D + He^3 \rightarrow He^4 + p + 18.3\ MeV$$

Because the fuel for the last two reactions is generated in the first two, only deuterium need be supplied externally. The final reaction products—ordinary helium and hydrogen—are benign, but the energetic neutrons can damage and induce radioactivity in the structure of the reactor.

Fusion based on *any* fuel cycle containing deuterium produces undesirable neutrons. The reason is this: Most of the deuterium can be made to "burn" in a desired reaction—for example, the benign D-He^3 fusion above, to produce ordinary helium, a proton, and energy. But some of the deuterium in the mixture will also collide with itself, producing neutrons and radioactive tritium; further collisions with the tritium will produce more neutrons.

Fuel cycles based on protons tend to produce far lower amounts of neutrons. The lithium-6 reaction

$$p + Li^6 \rightarrow He^3 + He^4 + 4.02\ MeV$$

is often considered because of the low charge of both constituents. But it is not completely neutron-free. A product (He^3) can react with Li^6 to produce neutrons via a low-probability, but nonetheless troublesome, side reaction.

From an engineering point of view, the boron-11 reaction

$$p + B^{11} \rightarrow 3He^4 + 8.68\ MeV$$

is nearly ideal. Neither the fuel *nor* the end products are radioactive. Furthermore, no neutrons capable of inducing radioactivity are produced.

Because all the products of the boron-11 reaction are charged, they could theoretically be harnessed to generate electricity directly, without the inherent waste of generating steam to run a turbine. However, the high electric charge of boron (it has 5 protons) makes the task of designing an energy-producing system very difficult.—*L.L.*

disadvantage. If this factor is added to the reactor's high initial cost, large size, and poor power density, D-T fusion becomes an unacceptable financial risk. The public perception of fusion as ultimately safer than fission cannot nullify this.

Furthermore, in a broader sense the safety of a D-T fusion reactor would depend on its being used responsibly. One of the best ways to produce material for atomic weapons would be to put common, natural uranium or thorium in the blanket of a D-T reactor, where the fusion neutrons would soon transform it to weapons-grade material. And tritium, an unavoidable product of the reactor, is used in some hydrogen bombs. In the early years, research on D-T fusion was classified precisely because it would provide a ready source of material for weapons. Such a reactor would only abet the proliferation of nuclear weapons and could hardly be considered a wise power source to export to unstable governments.

A major driving force behind fusion has been the promise of abundant fuel. Indeed, the fusion program was originally justified not on safety grounds—

The scientific goal of the fusion program turns out to be an engineering nightmare.

fission's safety was not widely doubted then—but because of the expected rapid depletion of uranium reserves. But this is no longer a major concern. One reason is the declining demand for additional fission power and hence for the uranium to fuel it. The earth's reserves of uranium are now known to be large enough to supply fission reactors for at least 50 to 70 years without fuel reprocessing.

There has also been a breakthrough in the technology for removing uranium from seawater. A Japanese consortium is starting up a pilot plant that uses an efficient filter to trap and concentrate the extremely dilute uranium in seawater. This technology will make available virtually unlimited supplies of uranium at a cost at most ten times the current (depressed) price for conventionally mined uranium. The cost of nuclear fuel is so small a fraction of the total cost of generating electricity that the new technology would increase electricity prices only negligibly. The same oceans that could supply fusion fuels can also supply fission fuel; the abundance of deuterium for fusion ceases to be a compelling argument.

Dim Prospects for D-T Fusion

In retrospect, it is not totally surprising that fusion should fare so poorly in comparison with fission. The problem is simply that in fusion, 80 percent of the energy is released in neutrons with an energy of 14 million electron volts (MeV) that travel about 50 centimeters. In fission, less than 3 percent of the energy is released in neutrons, and these have an energy of only 1 to 2 MeV. Most of the fission products are highly charged nuclei that travel less than .001 centimeter before coming to rest.

Thus, while the major radioactivity from fission is contained within the fuel pins, the major radioactivity from fusion would damage the reactor structure and create problems of complexity, unreliability, and size. While fission's numerous wastes pose problems of disposal and reactor safety, fusion's neutrons could easily be used to manufacture material for atomic weapons. It is hard to see why a utility in need of additional generating capacity would purchase a D-T fusion reactor instead of a contemporary LWR fission reactor. And as far as most utilities are concerned, even the LWR no longer seems a good choice.

The early history of the fission program was similar to current experience in the fusion program—except that success in fission came too easily. As soon as we found a concept that worked reasonably well, powerful forces drove that machine, the LWR, to prominence. We did not take the time to test, modify, and finally choose the "best" nuclear reactor among many competitors.

Now we know that safer, smaller, and probably cheaper fission reactors can be built. In fact, reactors could be small enough to be assembled in a factory and shipped via truck, reactors so safe that no operator error or even loss-of-coolant accident could cause release of radiation. The dreaded meltdown would also be impossible in these small, "modular" reactors. Such a reactor has been operating for 15 years in Germany. To be sure, this kind of reactor would probably not be the best choice in a world in which uranium was scarce and reprocessing and fuel breeding were necessary. But we do not live in such a world. Unfortunately, the resounding crash of the LWR has prejudiced the possibility of a new beginning for fission reactors.

The only real hope for fusion is to take the long view ignored in the fission program. Neutron-free fusion is a quintessential example of a high-risk, high-gain area of physics that *might* also provide a good answer to an engineering problem. We have no guarantee that an answer exists. But we know that if it does, it can meet the original goal of the fusion program—universally available, inexhaustible, environmentally benign power. Perhaps we should not be greatly troubled that our first attempt to develop such a marvelous thing will not be the success we had hoped. We can go on to seek a better alternative.

LAWRENCE M. LIDSKY, professor of nuclear engineering at M.I.T., is an associate director of the Plasma Fusion Center and editor of the Journal of Fusion Energy. *He has worked on plasma physics and fusion-reactor technology for 20 years.*

John A. Taube (415) 334-3733
55 Chumasero Drive #7E
San Francisco, California 94132
October 7, 1986

Dr. T. Connelly
Mechanical Engineering Department
Stanford University
Stanford, California 94305-3030

Dear Dr. Connelly:

I have written to you on two previous occasions and you were kind enough to have replied. I have a few additionally questions, and I hope that I am not abusing the courtesy you have extended to me in the past.

In all my reading on the nuclear question, the term nuclear waste is constantly used. It seems to me that this is not an appropriate term and that the appropriate term is nuclear by-product. Furthermore, it seems to me that this by-product has energy that the present state of the art cannot utilize and some time in the future, our remarkable scientists will ascertain precisely how to utilize this energy. Your comments on this point would be most appreciated.

I wonder if you have come across the enclosed TECHNOLOGY REVIEW, October, 1983 article: "The Trouble With Fusion." Its author is Dr. Lawrence M. Lidsky, professor of nuclear engineering at Massachusetts Institute of Technology. His contention is that even when the extraction of energy from nuclear fusion is resolved, the technology that will be required for fusion reactor plants will be prohibitive. I would appreciate your comments on it.

Enclosed also is a letter-to-the-editor of mine on the nuclear question. You will note that in this letter, I contend that the disposal of nuclear waste (?) has been resolved technically but not politically. Am I correct on this point? Your comments on this and the other points of the letter will be appreciated.

I have no credentials as a scientist. I am a citizen who realizes that extraneous energy -- non-human energy -- IS our civilization. Without a variety of sources of this energy, and the technology needed to utilize it, our modern civilization would not exist. I therefore spend considerable time attempting to understanding all aspects of the energy question.

Sincerely,

John A. Taube

John A. Taube

John A. Taube (415) 334-3733
55 Chumasero Drive #7E
San Francisco, California 94132
October 2, 1986

Letter to the Editor
SAN FRANCISCO EXAMINER
110 5th Street, Box 7260
San Francisco, California 94103

Dear Editor:

The Loran letter (Sept.30) on the nuclear issue, though very lengthy, was quite inaccurate.

Loran says that the disposal of nuclear waste has not been resolved. This is in contradiction to the Association of Engineering Geologists, a group of renown American scientists. A policy statement, adopted by their Board of Directors on June 27, 1980, stated that the solution to the disposal of high level nuclear waste is well within our current technology. To quote the text: "Technologies exist to ensure selection of disposal sites in these geologic media which can provide long term integrity without harmful effects due to migration of radioactive materials to the biosphere."

Encapsulating nuclear waste so that it can be permanently isolated and stored has been accomplished. It is extremely unfortunate that while this has been achieved technically, politically it has not. Politicians, bowing to the many power-wielding pressure groups, have been influenced to treat this matter as though a problem really exists. None does! The fear that people will suffer from radiation from this storage is unfounded.

Loran spoke of tailings from uranium mining. There is a natural ongoing decay from uranium which produces radon, and this process started when planet Earth formed. It is not man made. This radon, with a very short half-life, does not have an adverse health factor in the open air. In our homes, however, it is an entirely different matter. Because of the material that homes are built with, plus radon coming from the ground, the occupants of many of our homes get much more radiation than the people living near Three Mile Island got during the famous incident.

From a scientific viwpoint, the Three-Mile Island nuclear accident is ample evidence that a containment building is more than adequate to handle nuclear accidents of large magnitude. It is agreed amoung most scientists that the health problems and early deaths that are resulting from the Chernobyl accident would not exist if that nuclear reactor had a containment building.

Sincerely,

John A. Taube

TO:

I thought you might find this bit of trivia of interest, and something to add to your records on Howard Scott, the man.

Walt Fryers.

5/3/87

Excerpt from:

The intimate personal story behind the pioneering achievements of the world's most famous anthropologist . . .

BLACKBERRY WINTER
My Earlier Years
by Margaret Mead

(1972)

Her reminiscences of Howard Scott and Technocracy:

“ One of my troubled friends was Eleanor Steele, who was beautiful and amiable and also vulnerable because she was so pliant to other people's wishes. Just out of college she had fallen in love with Howard Scott, the magnetic founder of Technocracy. Howard was married, or so we believed. Later we learned how easy it was for people to make up stories about Howard. In any event, we believed that Howard had a wife, and he did have a mistress, an actress whom we saw perform in a magnificent presentation of King Lear, and then there was Eleanor. True to the style of our group, she made no bargains and asked for nothing. But once, two years before, when Luther and I had lent our flat to her and I had gone to work in Ogburn's office for the evening, Eleanor telephoned the wry comment, "When is a date not a date? When your lover's mistress won't let him keep it. Come home, he isn't coming."

By the time Reo and I came to New York, Eleanor had left Howard and was married to a perfectly conventional young man who worked for the telephone company and had installed her in a furnished apartment near the Museum. So Howard, who was just starting Technocracy, was at loose ends and spent a lot of time with us. I owe to those long talks a kind of inoculation against the pre-automation concepts of Marxism. It was from Howard that I learned about automation before the word came into our vocabulary.

He had a vision of a society in which people would work for

about fifteen hours a week for twenty years only, a society in which money would take the form of adjusted credits and in which spending money would provide an inventory of consumer needs and wants. He envisaged a house in which chairs would be stacked in a wall; when a visitor arrived he would give the number of his constitutional type and the appropriate chair would pop out. At a time when people were still thinking—as they still are—in terms of the limited resources of politically bounded nation-states, he thought in terms of continental masses and their aggregated resources.

He was an extraordinary person, well over six feet in height, gaunt and rangy, Irish and somehow a man of the frontier, endlessly inventive and prophetic. And very honest. In the terrible winter of 1933, when the banks closed and the country was in a panic, he was invited to speak at a very important dinner with a national radio hookup. Ruth Benedict wrote me what happened. There had been stories about him in the press for days and his name was on every tongue. It appeared that he could have had anything he advocated—and he did not even try. Instead, he made a miserable speech in which he said the time was not ripe. Later Howard explained to me that he knew the kind of society he advocated could not come into being yet. There would have to be experiments by the Left and experiments by the Right before people would give up the idea of an economy based on scarcity and recognize that with modern techniques of production the thing to do was to organize consumption. His estimate that every individual in the country would have a buying power—in services and products—equivalent to some $20,000 a year was an idea that interested my father, who arranged for him to speak at a special meeting of members of the Republican Club. But once again Howard stressed the difficulties and failed to explain how it could be done. This question of how it can be done still agitates knowledgeable bankers and businessmen who continue to think in the old terms of where the money will come from, rather than in terms of how often money changes hands for services.

In December, 1933, while Howard was away on an organizing trip, Eleanor fell seriously ill. I took her to stay with me, but even with the help of nurses I could not provide the kind of care she needed, and her physician would not put her into a hospital. Finally, I invoked the help of a friend who was a professor in a teaching hospital, but he said that if her own physician did not

make the decision, nothing could be done, unless . . . I gathered that if I said I would put her out on the street, then, under such circumstances, the niceties of medical ethics could be waived. We did get her into a hospital and there, a week later, she died of miliary tuberculosis, beautiful and considerate of others to the last. She was the first of our college group to die.

The hospital had found her a most puzzling patient, for her former husband appeared on the scene and made friends with her current lover, while all of us held our breath because Howard was in Chicago to address a mass meeting. She was buried by a long-suffering uncle, and her former husband drove me to the funeral in New Jersey. When Howard got back the day after the funeral, we walked all afternoon while I let him talk. About Eleanor, he said grandiloquently, "She was the Joan of Arc of Technocracy."

Two other people were present when Eleanor died, her friend Sara Bachrach and the artist Allen Ullman, to whom Sara had just become engaged. Sara and Allen won my affection forever that afternoon, for Allen did something I have never ceased to value. Coming in as a stranger, he supported Sara without making any of us feel that his presence was not completely appropriate. He had the gift of perfect presence, and he was one of the few men I have known who could take three women out together and make each of them feel contented, honored, and amused.

During the two years Reo and I lived in New York I saw a good deal of Howard Scott, but after that only once again. In the autumn of 1941, when Charles Lindbergh was holding the attention of many Americans with his prediction that Fascism was the wave of the future, Technocracy suddenly blazed forth with newspaper advertisements showing imposing cars and men in uniform standing at attention. It appeared to many people that Technocracy was turning into a form of Fascism, and I was asked to find out what I could. I invited Howard to dinner in a ground-floor apartment, leaving the shades up and wishing there were someone I could tell what I was doing. Howard talked freely. There was no sinister millionaire behind the movement and its goals were unchanged. The members of the organization had put their combined savings into that one set of huge advertisements in the hope of attracting a larger following. But very few people responded.

Recently I wrote something that caught the attention of the

small Technocracy headquarters in Seattle—for the movement still appeals to a group of people in the northwestern United States and Canada—and they sent me a little set of pamphlets dated twenty years ago.

At the height of his notoriety, Howard was attacked as an impostor who made all sorts of false claims about his activities and his training. In fact, he had only completed the ninth grade, but his prevision of the electronic revolution was extraordinary. His lack of mastery of the intermediate steps was one of his great handicaps and perhaps also the very vividness of his accounts of people he had never met, places he had never seen, and dams he had not built. Events that lived in his imagination became real to others, and later those who sought to destroy him accused him of fabrication. But he was not destroyed as a person, for he lived to a ripe old age, sustained by the faith of a few people. Had his education matched the scope of his imagination, would he, I have often wondered, have had a profound effect on the country, or was he a forerunner, a man born before his time?

During those early years, however, he made a great contribution not only to my thinking but also to our marriage. Although there were few people who did not arouse in Reo some echo of his emotion-laden past, this never happened with Howard. He was always welcome when he dropped by, after a hard day of map-making or working on calculations, to spend an evening with us. //

Notes:
Howard Scott died in 1970. This book was published two years later, in 1972. On page 287 Mead writes: "...those who died long enough ago so that, in writing about them, I can feel that I am writing about a past that now belongs to the next generation--Franz Boas and William Ogburn, Ruth Benedict, Edward Sapir, and A. R. Radcliffe-Brown, my grandmother and my mother and father, Eleanor Steele and Howard Scott, Jane Belo, Colin McPhee, and Walter Spies, and my youngest sister, Priscilla.....".

The "Reo" mentioned in the narrative was her second husband, Reo Fortune, a New Zealand phsychologist.

Margaret Mead wrote several books, principally about the primitive peoples of the South Seas. A review states:: "Here as elsewhere the emphasis is upon personal adventure and meaning rather than scientific discovery." It is not surprising then that she reveals a very limited understanding of Howard Scott, his work, and the concepts of Technocracy.

4/3/87 wf

W. R. Fryers